Possible use of quadrant antennas for clandestine shortwave broadcasting: A technical assessment of Cold War number station operations from Bulgaria

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23 May 2026

Extended and improved version of the original publication.

A retrospective RF propagation and antenna systems analysis

Subject:	Antenna suitability for clandestine HF broadcasting
Period:	Cold War era, approximately 1950–1989
Region:	Bulgaria (transmitter) to Central and Eastern Europe, Mediterranean, and Near East (reception)

This document presents a technical feasibility assessment only. All propagation calculations are based on publicly available antenna engineering data and standard ITU-R skywave propagation methodology. All primary sources cited are publicly available; where declassified government documents are referenced, these are accessed through official open archives.

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Abstract

No reliable documentary evidence has emerged in the open record concerning the operational infrastructure of the Bulgarian-attributed shortwave number stations S02 and E01, which were active during the Cold War period and into the mid-1990s. The intelligence and military archives that would settle the question of which transmitter sites, antenna types, and frequencies were used remain classified, destroyed, or otherwise inaccessible. This study therefore approaches the problem from the opposite direction: working backwards from what is known — the documented operating frequencies, the observed signal characteristics, and the inventory of low-power shortwave transmitter sites known to have existed in the Sofia region — to ask how technically plausible it is that any of those sites could have served as the origin of the transmissions in question.

Almost all Bulgarian shortwave transmitter sites known to have been associated with Cold War military and state security operations were equipped with Soviet-pattern horizontal dipole antennas designated VGDSh (*Vibrator Gorizontalny Dipol shuntirovanny*). This antenna family shares its fundamental operating principles with the Western quadrant antenna: both are horizontally polarised, low-mounted HF radiators that exploit near-vertical incidence skywave (NVIS) propagation for medium-range coverage. The VGDSh, however, is poorly documented in the open literature, with published amateur and engineering data showing material inconsistencies between sources. This study therefore uses the quadrant antenna—specifically the Wells cage quadrant and the single-wire cut-delta variant characterised by Beaumont, both of which are rigorously documented and electromagnetically modelled—as a technically equivalent and well-characterised proxy to derive propagation, link budget, and power conclusions applicable to both antenna families.

Three candidate transmitter sites in the Sofia region are assessed: Pobit Kamak (near Vakarel), Gorna Malina, and Momina Skala on Vitosha Mountain. Link budget calculations demonstrate that these sites, operating between 4.7 MHz and 7 MHz with transmitter powers in the 500 W to 1 kW class typical of standard Warsaw Pact fixed-installation HF equipment (well above the 5 W to 25 W theoretical minimum for digit intelligibility), could achieve reliable NVIS skywave coverage across an arc spanning Austria, Germany, Italy, Switzerland, Turkey, Greece, Cyprus, and Israel—consistent with the documented frequencies and signal characteristics of S02 and E01. The conclusions of this study are technical estimates, not historical facts, and it remains possible that the stations operated from sites that are entirely unknown. The most accurate description of what follows is: given the available technical evidence, this is the most probable version of the story.

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1 Introduction

1.1 Number stations: background

Number stations are clandestine shortwave broadcasting services, typically operated by state intelligence agencies, which transmit sequences of spoken digits, phonetic letters, or Morse code groups. These transmissions serve as a one-way communications channel to field agents or foreign assets, who decode the message using a pre-arranged one-time pad (OTP). The inherent asymmetry of the channel—the receiver need never transmit and therefore cannot be triangulated—made this method operationally attractive throughout the Cold War era and beyond.

Although the precise origins and operators of most number stations remain a matter of scholarly inference rather than confirmed public record, signals intelligence researchers, most notably through the Enigma Control (ENIGMA 2000) catalogue and the publications of the Shortwave Listening community, have attributed a significant fraction of documented number stations to Eastern Bloc intelligence services, including the Bulgarian Darzhavna Sigurnost (DS, State Security) and its Soviet-coordinated counterparts. The physical characteristics of such transmissions—operating frequency, modulation mode, transmission schedule, and apparent geographic origin—are consistent with sites operating in the Sofia region of Bulgaria.

1.2 Scope and objectives

This study addresses the following technical questions:

1. The Bulgarian transmitter sites known to be associated with Cold War intelligence operations were equipped with VGDSh horizontal dipole antennas. Because VGDSh technical specifications are inconsistently documented in the public domain, this study uses the quadrant antenna—which shares the same physical operating principles and is rigorously characterised in the open literature—as a proxy. To what extent are the propagation and power conclusions derived from the quadrant applicable to the VGDSh installations at these sites?

2. What transmitter powers would have been required to achieve digit intelligibility for a trained agent at destinations in Central Europe, the Mediterranean, and the Near East, using ordinary shortwave receivers with single-sideband (SSB) or narrowband amplitude modulation (AM)?

3. Which of the three identified candidate transmitter sites—Pobit Kamak (Vakarel), Gorna Malina, and Momina Skala—offered the most favourable operational characteristics for this purpose?

1.3 Epistemic status and limitations of this study

The conclusions presented in this document are technical estimates, not historical facts. The authors cannot travel back in time, access operational archives that remain classified or destroyed, or directly verify the equipment configurations, transmission schedules, or site assignments of the Bulgarian number stations under study. No primary-source documentary evidence has been located that explicitly identifies any specific transmitter site as the origin of broadcasts attributed to S02 or E01, nor that confirms the precise antenna type, transmitter power, or operating frequency at any candidate site during the relevant operational period.

What this study does is assemble the best available open-source technical evidence — satellite imagery, published antenna engineering data, standard propagation modelling, and the documented operational characteristics of the stations as recorded by independent shortwave monitoring organisations — and asks whether the identified candidate sites are *technically consistent* with the observed transmission characteristics. The answer, as developed in the following sections, is that they are. But technical consistency is not proof of operational use.

It is entirely possible that the number stations attributed to Bulgaria operated from transmitter sites that remain unknown, using equipment or configurations not considered here. The three candidate sites discussed in this study — Pobit Kamak, Gorna Malina, and Momina Skala — are assessed as the most probable locations on the basis of the technical evidence available, but the authors make no claim of certainty. The most accurate characterisation of the conclusions of this study is: *given what is known about the sites, the antennas, and the propagation physics, this is what the most probable version of events looks like.* Readers should weigh the evidence accordingly and draw their own conclusions.

2 Antenna systems: VGDSh, the quadrant, and the analytical proxy approach

2.1 The VGDSh at Bulgarian transmitter sites and the problem of open-source documentation

All shortwave transmitter sites in Bulgaria identified as associated with Cold War military or intelligence operations—including the candidate sites at Pobit Kamak, Gorna Malina, and Momina Skala, as well as the high-power installations at Kostinbrod, Padarsko, and Stolnik—were equipped with Soviet-pattern VGDSh horizontal dipole antennas, as is consistent with Warsaw Pact HF transmission doctrine for this class of installation (see Section 2.6 for a detailed comparison). The VGDSh is the standard Soviet horizontal HF dipole; its presence at Bulgarian military sites is corroborated by the architecture of contemporary Soviet SRF and Long-Range Aviation (LRA) transmitter stations documented in declassified CIA technical intelligence reports [5].

However, the VGDSh presents a significant problem for open-source technical analysis: its engineering parameters are poorly and inconsistently documented in the public domain. Amateur radio operators who have published measurements or calculations of VGDSh antennas report figures that differ materially from one another in gain, feed point impedance, and elevation pattern characteristics. No single authoritative, peer-reviewed, or rigorously modelled open-source characterisation of the VGDSh at shortwave frequencies is available to the authors.

This study therefore adopts the following analytical approach: the quadrant antenna, which shares the same fundamental operating principles as the VGDSh—horizontal polarisation, low mounting height in terms of wavelength, and NVIS-dominated propagation at the frequencies of interest—is used as a technically equivalent, rigorously documented proxy. The quadrant is characterised in a publicly available technical report by Beaumont [8] using validated NEC electromagnetic modelling, and its parameters are therefore reproducible and verifiable. Conclusions derived from the quadrant analysis are then mapped to the VGDSh context, with the differences between the two antenna types explicitly noted and their operational significance assessed.

2.2 Wells cage quadrant

The quadrant antenna in its canonical form was described by Wells in 1944 [6] as a horizontally polarised, quasi-omnidirectional radiator for the shortwave bands, employing two multi-wire cage arms of half-wavelength ($\lambda/2$) each, arranged at 90° in the horizontal plane. The cage construction—employing multiple wires in a cross-shaped or star spreader arrangement—reduces the drive point impedance from the nominally high value of a single-wire $\lambda/2$ resonant element (typically $\approx 5{,}000\,\Omega$ at resonance) to a practically manageable value around $600\,\Omega$, whilst simultaneously broadening the operational bandwidth to approximately an octave. Wells noted the theoretical possibility of single-wire

construction but did not pursue it owing to the narrow bandwidth and high drive point impedance [8].

The principal electrical parameters of the Wells cage quadrant at 7.15 MHz, as modelled by Beaumont using EZNEC Pro/2 (a commercial implementation of the Numeric Electromagnetic Code, NEC) [8], are reproduced in Table 1.

Table 1: Principal electrical parameters of the Wells cage quadrant at 7.15 MHz, after Beaumont (2015).

Parameter	**Value**
Operating frequency (design centre)	7.15 MHz
Maximum gain	6.0 dBi
Elevation angle at maximum gain	60°
Drive point impedance	$(608 + j4)\,\Omega$
Azimuth pattern	Quasi-omnidirectional
VSWR bandwidth (≤ 1.25)	7.0 MHz to 7.3 MHz
Polarisation	Horizontal
Recommended mounting height	$\lambda/4$ above ground

The commercial broadcast-grade HQ quadrant, as specified by Ampegon and Transradio SenderSysteme Berlin [9], extends this concept to a multi-dipole cage design supporting operation across two adjacent shortwave broadcasting bands (spanning 5.9 MHz to 26.1 MHz), with a published gain of 7 dBi, a balanced input impedance of 300 Ω, and a maximum rated carrier power of 500 kW.

2.3 Single-wire cut-delta quadrant

Beaumont [8] describes a lightweight amateur variant, designated the *single-wire cut-delta quadrant*, in which the cage arms are replaced by single conductors and the feed arrangement uses a delta-matched section (also known as a cut-delta) to achieve a practical drive point impedance. Key computed parameters at 7.15 MHz for this antenna suspended at $5\lambda/12$ above average ground (conductivity 10 mS m^{-1}, dielectric constant 13) are:

> Maximum gain: 5.4 dBi; azimuth variation at 35° elevation: ±0.9 dB; drive point impedance: $(606 - j3)\,\Omega$ at resonance; VSWR bandwidth (≤ 2): 6.9 MHz to 7.4 MHz.

Beaumont further notes that suspension at $5\lambda/12$ height was chosen specifically to illustrate coverage to distances of approximately 1,500 km, corresponding to a single ionospheric hop, at approximately constant field strength independent of distance. For a 7 MHz installation, this equates to a physical height of approximately 17.5 m, attainable with modest lattice masts or fortuitously positioned tall structures.

The antenna requires three suspension points in a right-angled triangular plan configuration, a balun transformer (which may be pole-mounted near ground level), and no elaborate ground screen. This simplicity is operationally significant: the antenna can be erected within a compact site perimeter and, in its single-wire form, presents far lower visual, wind-loading, and electromagnetic signature than a large directional curtain array.

2.4 Stacked quadrant configurations

For operation at the upper end of the shortwave spectrum (21 MHz and above), Beaumont [8] describes stacked variants in which two quadrant tiers, separated vertically by $\lambda/2$, are driven in phase. The stacked Wells cage quadrant at 21.225 MHz achieves 9.6 dBi maximum gain at a 17° takeoff angle, substantially suppressing high-angle NVIS radiation in favour of lower-angle skywave suitable for ranges in excess of 2,000 km. Stacked single-wire quadrants at the same frequency achieve 8.4 dBi. These configurations would be relevant if the operational requirement extended to more distant targets such as Israel or Cyprus, as discussed in Section 4.

2.5 Operational bandwidth of the cage quadrant and VGDSh

The question of how wide a frequency range the cage quadrant and VGDSh can cover in practice is operationally important and deserves explicit treatment, since these antennas are described in both Western and Soviet sources as *broadband* — a claim that requires careful qualification.

The physical basis of broadband behaviour

The bandwidth of a resonant antenna is inversely proportional to its Q factor. A thin single-wire element has a high Q — it accepts power efficiently only over a narrow band around its resonant frequency, and the drive-point impedance rises or falls steeply as the frequency moves away from resonance. The cage construction fundamentally changes this: replacing a single wire with a bundle of parallel wires arranged around a circular spreader forms a structure whose effective electrical diameter is much larger than any individual wire. This large diameter-to-length ratio reduces the Q of the element, which has two consequences. First, the drive-point impedance changes more slowly with frequency, so the antenna remains acceptably matched to its feeder over a wider frequency range. Second, the radiation pattern degrades more gradually at off-resonance frequencies. Both effects contribute to the broadband behaviour.

Bandwidth of the single-wire cut-delta quadrant

The single-wire cut-delta variant characterised by Beaumont [8] at a design frequency of 7.15 MHz achieves a VSWR ≤ 2 bandwidth of 6.9 MHz to 7.4 MHz — a span of 500 kHz,

or approximately 7 % of the centre frequency. This is a narrowband result, consistent with the high Q of a thin single-wire element. Beaumont explicitly notes the narrow bandwidth as one of the principal weaknesses of the single-wire variant compared to the cage construction, and the reason Wells himself did not pursue the single-wire approach in his original 1944 work [6].

Bandwidth of the Wells cage quadrant and VGDSh

The cage construction — whether in the Wells quadrant form or the Soviet VGDSh — achieves qualitatively different behaviour. Beaumont reports that the cage quadrant maintains a satisfactory radiation pattern and acceptable VSWR across approximately *one octave*, i.e. a 2:1 frequency ratio [8]. The antenna.be specification for the commercial HQ broadcast quadrant confirms this: the design is rated for operation across two adjacent shortwave broadcasting bands, spanning 5.9 MHz to 26.1 MHz in its multi-dipole stacked form [9], though individual single-dipole HQ units cover a more limited sub-range of this spectrum.

For a cage quadrant or VGDSh designed for a centre frequency of 7 MHz, one octave of usable bandwidth corresponds to a coverage range of approximately 5 MHz to 10 MHz. This is a result of considerable operational significance: it means that a *single fixed antenna installation* — with arms cut for 7 MHz — can serve transmissions across the entire 6 m band, the 7 MHz amateur band, the 9 MHz tropical broadcasting band, and reach into the 9.4 MHz–9.9 MHz shortwave broadcasting band, without any physical retuning or modification of the antenna structure. The transmitter's output network and antenna tuning unit (ATU) may require adjustment between frequencies, but the antenna itself radiates efficiently across the entire octave.

Relationship to the documented operating frequencies of S02 and E01

The documented operating frequencies of the Bulgarian-attributed number stations S02 and E01 — 4.74 MHz, 5.5 MHz, and 6.675 MHz [17, 18] — span a range of approximately 4.7 MHz to 6.7 MHz, a ratio of 1.42:1. This is well within the one-octave (2:1) bandwidth of a cage antenna designed for any centre frequency in the 5 MHz to 6 MHz range. An antenna with arms cut for approximately 5.5 MHz would cover all three documented frequencies within its usable bandwidth without retuning. Equally, an antenna designed for 7 MHz — the most common design frequency for this class of antenna, and directly supported by the shadow-comparison height estimate at Pobit Kamak — would cover the documented frequencies at the lower end of its octave bandwidth, from approximately 5 MHz upward.

This bandwidth analysis therefore provides an additional and independent line of evidence linking the identified candidate sites to the documented operating characteristics of the

Bulgarian number stations: a single cage VGDSh installation of the type and dimensions observed at Pobit Kamak and Gorna Malina is, without modification, capable of covering all known operating frequencies of S02 and E01 within a single antenna design.

2.6 The Soviet analogue: VGDSh horizontal dipole and its relationship to the quadrant

As established in Section 2, the VGDSh is the antenna type actually installed at the Bulgarian sites under study, whilst the quadrant serves as the analytical proxy from which this study derives its numerical conclusions. This subsection documents the technical relationship between the two antenna types, establishes the validity of the proxy approach, and identifies the single operational difference that makes the quadrant superior to the VGDSh for the specific task of multi-bearing agent communications.

The VGDSh family: VGD, VGDSh, and VGDSh-2U

The Soviet VGDSh designation is a compound abbreviation: *V* for *Vibrator* (radiating element), *G* for *Gorizontalny* (horizontal), *D* for *Dipol* (dipole), and *sh* for *shuntirovanny* (shunted), indicating a shunted or shunt-fed variant. Russian-language engineering and amateur radio sources confirm that the VGD (without the *sh* suffix) and the VGDSh are distinct antennas: the former was proposed by Nadenenko for receiving installations, whilst the VGDSh—designed by G.Z. Aizenberg and V.D. Kuznetsov—was the standard transmitting-site antenna, distinguished by its shunted feed arrangement which lowers the drive point impedance and matches it to 600 Ω open-wire feeders used at transmitter stations [2]. Russian operators explicitly describe the VGDSh as *antenna zenitnogo izlucheniya*—a zenith-radiation antenna—confirming its primary operational role is NVIS propagation [3]. A contemporaneous account of Soviet jamming infrastructure confirms a further operational use of the VGDSh: Pleikys documents that local ground-wave jamming stations, with transmitter powers of 1–20 kW and effective ranges of approximately 30 km, used the *"standard multi-wire broadband VGDSh type dipole"* as their standard antenna [1]. In this ground-wave role the antenna was apparently reoriented away from the standard horizontal mounting—the Pleikys source illustrates a captioned photograph of such a unit described as used for ground-wave jamming, though precise engineering data on the tilt angle and feed-point adaptation employed are not given in publicly available sources (see Section 3.5 for a detailed analysis of the implications). This confirms that the VGDSh family was sufficiently versatile to serve in both NVIS skywave and ground-wave configurations depending on mounting orientation, further corroborating the broad operational relevance of the antenna type at the Bulgarian sites under study.

Critically, the VGDSh family is not limited to a single-dipole configuration. A declassified CIA intelligence report on Soviet Strategic Rocket Forces (SRF) transmitter stations [5] inventories three distinct variants at Soviet military HF sites:

> VGD: simple horizontal dipole (receiving sites); VGDSh: shunted horizontal dipole (transmitting sites, single element); VGDSh-2U: dual shunted-angle dipole (transmitting sites, two elements).

The VGDSh-2U designation—translated by the CIA as "dual shunted-angle dipole"—is architecturally significant. Two dipole elements at 90° to each other, mounted on a common support, constitute a configuration structurally identical to a turnstile antenna. When fed in phase quadrature (90° phase difference between the two elements), a turnstile produces an azimuth radiation pattern that deviates from true omnidirectionality by only ±5 %—closely comparable to the quadrant's ±0.9 dB variation [4]. Field reports from Russian amateur operators confirm VGDSh installations with two dipoles on a single mast, fed symmetrically, explicitly described as providing zenith radiation (NVIS) with coverage "in all directions" [3]. The CIA document also lists the quadrant as a separate, further-distinct antenna type at the same SRF sites, confirming that Soviet engineers recognised and deployed all three configurations for different operational requirements.

Structural and electrical comparison of the full antenna family

Table 2 presents the complete comparison across the VGDSh family and the quadrant, reflecting the range of configurations actually deployed at Soviet-pattern shortwave sites, including Bulgarian installations.

Feed-point impedance: why the three antenna types differ

The substantial differences in drive-point impedance between the VGDSh, the VGDSh-2U, and the quadrant are not arbitrary—they follow directly from the electrical topology of each design and the position of the feed point relative to the standing-wave current and voltage distribution on the radiating elements.

VGDSh: $\approx 73\,\Omega$ radiation resistance. The VGDSh is a single horizontal $\lambda/2$ dipole. At resonance, a centre-fed half-wave dipole presents a feed-point impedance of approximately $73\,\Omega$ [8], because the feed point sits precisely at the current maximum—and therefore the voltage minimum—of the standing wave pattern on the element. At this point the ratio of voltage to current (which is what impedance measures) is at its minimum, yielding the characteristic $73\,\Omega$ radiation resistance that follows from the geometry of the electromagnetic field distribution around a half-wave radiator. The *shuntirovanny* (shunted) feed arrangement of the VGDSh is a deliberate modification: a shunt element connected across the feed point transforms the $73\,\Omega$ radiation resistance to match the $600\,\Omega$ open-wire balanced feeders standard at Soviet transmitter installations [2]. The underlying dipole physics is unchanged; the shunt network performs an impedance transformation at the terminal.

Table 2: Comparison of the Soviet VGDSh antenna family and the Western quadrant. All are horizontally polarised HF antennas sharing the same NVIS propagation mechanism. Azimuth pattern is the principal operational variable.

Property	**VGD / VGDSh**	**VGDSh-2U**	**Quadrant**
Configuration	Single horizontal dipole	Two dipoles at 90°, common mast	Two arms at 90°, horizontal plane
Electrical length	$\lambda/2$ per element	$\lambda/2$ per element	λ total
Azimuth pattern	Bi-directional; two lobes with $\approx -20\,\mathrm{dB}$ nulls off wire ends	Near-omnidirectional ($\pm 5\,\%$) when fed in quadrature	Near-omnidirectional ($\pm 0.9\,\mathrm{dB}$)
Drive impedance	$\approx 73\,\Omega$	≈ 40–$50\,\Omega$ combined	$(608 + j4)\,\Omega$ (cage); $\approx 5{,}000\,\Omega$ (single wire, unmatched)
Feed arrangement	$600\,\Omega$ open-wire balanced line	Phase-quadrature feed or self-phasing by arm-length offset	Delta match, cage, or stub
Full 360° coverage	No	Yes (with quadrature feed)	Yes
DF susceptibility	Moderate (nulls usable)	Low (near-zero gradient)	Very low (near-zero gradient)
NVIS capable	Yes	Yes	Yes

VGDSh-2U: ≈ 40–$50\,\Omega$ combined. The VGDSh-2U places two $\lambda/2$ dipoles at 90° on a common mast, each fed independently. Each element individually presents $\approx 73\,\Omega$ at its own centre feed point, for the same reason as the single VGDSh above. However, the two crossed elements are in close proximity and interact electromagnetically: mutual coupling between orthogonal dipoles modifies the self-impedance of each element. For two crossed half-wave dipoles at the same height, the mutual impedance is predominantly resistive and reduces the effective impedance of each element below its free-space value. When the two elements are fed in parallel with a phase-quadrature arrangement, the combined

drive-point impedance falls to approximately 40 Ω to 50 Ω—broadly consistent with a parallel combination of two modified ≈ 73 Ω elements with mutual coupling losses taken into account [7].

Quadrant: ≈ 600 Ω (cage construction). The quadrant is topologically a full-wave antenna—total radiating length λ, bent at 90° at the feed point. This is the critical distinction. A full-wave centre-fed antenna presents its feed point at a *voltage maximum* (current minimum) of the standing wave pattern, which is the opposite of the half-wave dipole case. At a current minimum the ratio of voltage to current is at its maximum, producing a very high feed-point impedance—theoretically approaching ≈ 5,000 Ω for a single thin wire [8]. The cage construction—multiple parallel wires arranged around circular spreader insulators to form a tubular bundle of large effective diameter—introduces additional distributed capacitance along the arm length. This capacitance shifts the current and voltage distribution on the element, moving the effective current maximum closer to the feed point and reducing the feed-point impedance substantially. For the Wells cage design at 7.15 MHz, the NEC model computed by Beaumont yields $(608 + j4)\,\Omega$ [8]—a value that falls conveniently close to the 600 Ω characteristic impedance of open-wire balanced feeders, allowing a direct match without a transformer. The single-wire cut-delta variant achieves the same result through a different mechanism: the delta-match section acts as a $\lambda/4$ impedance-transforming transmission line, inverting the high impedance at the wire ends down to a practical drive-point value [8].

In summary: the VGDSh and VGDSh-2U are inherently low-impedance antennas because they feed at current maxima of half-wave elements, and require a shunt or transformer network to reach 600 Ω. The cage quadrant is inherently a high-impedance antenna because it feeds at a voltage maximum of a full-wave structure, and the cage geometry itself performs the impedance reduction to 600 Ω without a separate matching network.

NVIS capability: identical conclusions across the entire family

All members of the VGDSh family and the quadrant share the single property that governs NVIS performance: they are horizontal antennas suspended at low height above ground in terms of wavelength. For any horizontal antenna at mounting height $h \leq \lambda/4$, the elevation pattern peaks near the zenith, producing full NVIS radiation. At $h = \lambda/2$, the maximum shifts to approximately 30° elevation, transitioning to oblique skywave. This relationship is entirely independent of azimuth geometry and applies identically to the single-dipole VGDSh, the crossed VGDSh-2U, and the quadrant. The Russian operator literature explicitly designates the VGDSh as a zenith-radiation antenna [3], confirming that Soviet engineers designed and deployed it with precisely this propagation mechanism in mind.

All link budget figures, minimum power calculations, and NVIS coverage conclusions de-

rived in this study from quadrant parameters are therefore directly applicable to whichever variant of the VGDSh family was installed at the Bulgarian candidate sites. The azimuth pattern—the one property that varies across the family—does not affect the elevation pattern, the path loss, or the required transmitter power. It affects only the bearing coverage: a single-element VGDSh requires careful wire orientation to avoid placing primary targets in the end nulls, whilst the VGDSh-2U and the quadrant provide full omnidirectional coverage without this constraint.

Two further points deserve explicit statement here, as they bear directly on the interpretation of the site evidence presented in Section 3.

First, the VGDSh and the VGDSh-2U are *identical* in their NVIS performance. The crossed configuration of the VGDSh-2U confers no elevation pattern advantage whatsoever over the single VGDSh. Both antennas are horizontal, both are suspended at the same height, and the elevation pattern of a horizontal antenna is governed entirely by that height — not by whether the arms cross or point in a single direction. An operator choosing between a VGDSh and a VGDSh-2U for NVIS work was making a decision purely about azimuth coverage uniformity, not about NVIS capability. The single VGDSh is fully NVIS-capable; it simply illuminates different compass directions unequally.

Second, the directionality of the single VGDSh is considerably softer in practice than the theoretical $-20\,\mathrm{dB}$ end-null figure might suggest. The $-20\,\mathrm{dB}$ null of a $\lambda/2$ dipole occurs only at the exact wire-end bearing — precisely $0°$ and $180°$ relative to the wire axis. As the bearing moves away from the wire ends, the pattern level rises steeply: at $30°$ off the end-null the pattern is already only a few dB below the broadside maximum, and by $45°$ the element is well within its useful coverage region. The cage construction of the VGDSh — multiple parallel wires forming a cylindrical bundle — has no effect on this azimuth pattern; the cage is an impedance and bandwidth engineering device, and the radiation pattern is determined by the electrical length and geometry of the radiating element, not by its physical thickness or wire count. The practical consequence is that the VGDSh should not be thought of as a sharply directional antenna: it is better described as having a moderately preferred broadside direction, with usable signal available across a wide arc and only a narrow cone of genuinely poor coverage at the wire ends. Agents located somewhat off the broadside direction would receive a reduced but still operationally useful signal, and only those sitting nearly in line with the wire would experience the full depth of the null.

Summary of the East–West parallel

The Soviet VGDSh family and the Western quadrant represent parallel engineering traditions that independently arrived at the same operational insight: a horizontal dipole or dipole array suspended at low height is the most practical antenna for reliable medium-range NVIS communication without high towers, directional curtain infrastructure, or

ground radial systems. The progression within the VGDSh family—from the single VGDSh to the crossed VGDSh-2U—mirrors the Western progression from the simple dipole to the quadrant: in both cases, bending or crossing a second dipole at 90° to the first fills the azimuth nulls of the single-element configuration and achieves near-omnidirectional horizontal coverage. The quadrant achieves this through a full-wave bent geometry; the VGDSh-2U achieves it through crossed half-wave elements with phase quadrature feeding. The propagation performance of both is equivalent; the engineering route differs.

Since it cannot be determined from available open sources precisely which variant of the VGDSh family—single-element or dual-element—was installed at each Bulgarian candidate site, and since the quadrant is the most rigorously documented antenna of this class in the open literature, all numerical conclusions of this study are stated in terms of the quadrant and apply without qualification to any member of the VGDSh family at the same mounting height and frequency.

3 Candidate transmitter sites

Four sites in the Sofia region have been identified as associated with Cold War Bulgarian military, state security, or civil broadcasting radio transmission facilities. Their coordinates, extracted from satellite imagery and published technical records, are given in Table 3. All four lie within approximately 60 km of Sofia city centre. In addition, a fifth site within the city itself—on the roof of a building at Slaveykov Square—carries the same type of antenna infrastructure but is assessed as a local ground-wave jammer rather than a number station candidate (Section 3.4).

Satellite imagery of the three primary candidate sites (Pobit Kamak, Gorna Malina, and Momina Skala) confirms the presence of mast structures exceeding 10 m in height. This is directly significant to the antenna engineering analysis that follows: for operation at 7 MHz, the recommended mounting height of the quadrant antenna is approximately $\lambda/4 \approx 10.7$ m, with $\lambda/2 \approx 21.4$ m being preferred for the best low-angle radiation pattern (Section 2). The observed mast heights at all three sites are therefore consistent with, and physically sufficient for, the suspension of a quadrant antenna tuned to the 7 MHz amateur and broadcasting bands. A fourth site, Kostinbrod, is discussed separately in Section 3.6 as a high-power facility whose primary Cold War function was likely jamming rather than covert one-way broadcasting.

3.1 Pobit Kamak, near Vakarel (42.585°N, 23.641°E)

This site lies on elevated terrain approximately 35 km south-east of Sofia. Satellite imagery indicates cleared land with infrastructure consistent with a former radio installation. The elevated position offers a clear horizon to the north-west, the primary bearing towards Central Europe.

A photographic analysis of the site provides an independent estimate of the antenna suspension height. By comparing the cast shadows of the feeder pillars—whose dimensions are known from the standard VGDSh pillar construction—with the shadows of the masts visible in site imagery, the height of the antenna structure can be estimated by direct proportion. This shadow-comparison method yields an antenna height exceeding 16 m but apparently below 20 m. The most probable value therefore lies in the range 16 m to 20 m. This is directly consistent with the theoretical suspension height of $5\lambda/12 \approx 17.5$ m derived by Beaumont [8] for a 7 MHz quadrant optimised for single-hop NVIS coverage to approximately 1,500 km, and with the broader $\lambda/4$–$\lambda/2$ mounting range (10.7 m to 21.4 m at 7 MHz) discussed in Section 2. The observed mast height thus independently corroborates the antenna engineering case for 7 MHz NVIS operation at this site.

Satellite imagery of the Pobit Kamak installation reveals *two* separate VGDSh antennas, both deployed in collinear configurations—straight horizontal dipoles rather than bent quadrant geometries. This identifies both as single-element VGDSh variants. As noted above, this has no bearing on NVIS capability: both antennas radiate strongly at steep

Table 3: Radio transmission sites in the Sofia region and wider Bulgaria considered in this study. The Slaveykov Square entry is included as a negative example (local jammer); see Section 3.4. Sites in the lower group are assessed as implausible number station candidates and are discussed in Section 3.7.

Site designation	**Latitude (N)**	**Longitude (E)**	**Elev.**	**Role assessed**
Pobit Kamak (Vakarel)	42°34′5.7″	23°38′25.8″	∼680 m	Number station candidate
Gorna Malina	42°41′51.2″	23°40′53.4″	∼560 m	Number station candidate
Momina Skala (Vitosha)	42°37′32.1″	23°14′51.9″	∼1,250 m	Number station candidate
Slaveykov Sq., Sofia	42°41′33.7″	23°19′24.9″	∼570 m	Local RFE jammer (urban)
Kostinbrod	42°48′33.6″	23°11′3.7″	∼540 m	Civil Bcast / Jamming
Padarsko (Plovdiv)	42°13′48.0″	24°31′12.0″	∼160 m	Civil Bcast / Jamming
Stolnik	42°25′12.0″	23°21′0.0″	∼550 m	Civil Bcast / Jamming
Kozarevets	43°7′40.5″	25°49′5.6″	∼210 m	Jamming (excluded)
Grivitsa	43°24′18.1″	24°45′27.2″	∼100 m	Jamming (excluded)
Varna	43°8′50.5″	27°52′42.4″	∼20 m	Possible; relay impractical
Kocherinovo	42°2′48.1″	23°2′55.2″	∼490 m	Jamming (excluded)
Mogila	42°23′38.8″	25°42′15.7″	∼210 m	Jamming (excluded)
Stamboliyski	42°8′24.6″	24°32′22.3″	∼190 m	Jamming (excluded)

elevation angles at the observed suspension height and are fully capable of NVIS skywave propagation at 7 MHz. What the collinear deployment determines is the azimuth pat-

tern of each antenna individually: a straight horizontal dipole produces two broad lobes perpendicular to the wire and deep nulls of approximately −20 dB off the wire ends [7].

The two antennas are oriented differently, and their combined azimuth coverage is operationally significant.

Antenna 1 is oriented approximately north-west to south-east. Its two lobes therefore point north-west and south-east. The north-west lobe covers the primary Central European target arc: Austria, Germany, Switzerland, northern Italy, and the Czech Republic, all lying within 800 km to 1,400 km on bearings of approximately 295°–320° from the site. The reciprocal south-east lobe covers the Black Sea region, western Georgia, and north-western Turkey.

Antenna 2 is oriented approximately north-north-east to south-south-west, with the axis skewed slightly towards north rather than true north-east. Its two lobes therefore point north-north-east and south-south-west. The north-north-east lobe covers Poland, the Baltic states (Lithuania, Latvia, Estonia), Belarus, and potentially south-western Russia and Scandinavia, on bearings of approximately 10°–30°. The south-south-west lobe, pointing at approximately 190°–250°, covers a remarkably diverse and operationally valuable target set: southern Italy (Calabria, Sicily) at approximately 240°–248° and 900 km to 1,100 km; Albania at approximately 255°; Greece and the northern Aegean at approximately 220°–235°; Malta at approximately 240°; and the North African littoral—Tunisia, north-eastern Algeria—at approximately 225°–235° and 1,300 km to 1,600 km.

Taken together, the two antennas at Pobit Kamak provide complementary azimuth coverage spanning from North Africa and the central Mediterranean basin in the south-west, through the Balkans, Central Europe, and the Baltic states to the north-east— essentially the full arc of countries in which a Bulgarian intelligence service could plausibly have been running agents during the Cold War period. The gaps left by the nulls of one antenna are substantially filled by the lobes of the other. This two-antenna arrangement achieves broad directional coverage without requiring the more complex VGDSh-2U or quadrant configuration, at the cost of operating two separate antenna systems. Whether the two antennas were fed simultaneously from separate transmitters on separate frequencies, or used alternately, cannot be determined from available open-source evidence; simultaneous operation on the same frequency from two co-located dipoles would require careful phasing to avoid mutual interference.

3.2 Gorna Malina (42.698°N, 23.682°E)

Situated on the Sofiysko Pole (Sofia Plain) approximately 30 km north-east of Sofia, this site benefits from flat surroundings with good ground conductivity typical of cultivated plain. Its relatively low elevation provides no topographic shielding, and the flat terrain favours ground-wave coupling at the antenna base, improving the effective radiation of near-vertical incidence skywave (NVIS) at the lower shortwave bands.

As at Pobit Kamak, satellite imagery of the Gorna Malina site suggests a collinear arm deployment—a straight horizontal dipole rather than a bent quadrant geometry—identifying the antenna as a single-element VGDSh. The same considerations apply: the NVIS elevation pattern is unaffected by arm orientation and the antenna remains fully capable of steep-angle skywave radiation at the observed suspension height. However, the azimuth pattern is bidirectional, with broad lobes perpendicular to the wire and deep nulls off the wire ends.

From Gorna Malina, the bearing to Central Europe lies to the north-west at approximately 300°–315°, and to the Eastern Mediterranean to the south-south-east at approximately 135°–155°. The geometry is broadly similar to Pobit Kamak, and the same constraint applies: a single dipole cannot simultaneously place both target arcs in its lobe maxima. As with Pobit Kamak, the precise wire orientation has not been confirmed from available open-source imagery, and determining it would require either higher-resolution satellite imagery or ground-level photographic records of the installation during its operational period.

3.3 Momina Skala, Vitosha Mountain (42.626°N, 23.248°E)

At approximately 1,250 m above sea level on the southern slopes of Vitosha, this site offers the greatest elevation of the three. The Vitosha massif forms a prominent topographic feature to the south of Sofia, visible from a wide area. An elevated antenna site at this location benefits from reduced near-field ground losses and an unobstructed radiation path to the north-west—towards Austria, Germany, Switzerland, and Italy—and to the east-south-east towards Turkey and the Levant. The combination of natural elevation and westerly horizon clearance is particularly advantageous for NVIS propagation at 7 MHz to 9 MHz.

3.4 Slaveykov Square, Sofia (42.692,7°N, 23.323,6°E): a probable local jammer site

A rooftop installation at a building on Slaveykov Square in central Sofia has been identified from archival sources and historical satellite imagery as having carried the same pattern of antenna infrastructure as the primary candidate sites discussed above. The building is located at approximately 42°41′33.7″N, 23°19′24.9″E, in a dense residential and administrative urban district less than 2 km from Sofia city centre. The antenna installation and all associated equipment were removed during the 1990s and no physical trace of the transmission facility remains at the site today.

This site is assessed as *not* a candidate for number station operations, for three independent and mutually reinforcing reasons.

First, the urban environment imposed severe constraints on any covert shortwave transmission intended to reach agents at intercontinental or even trans-European distances.

Buildings, power infrastructure, and metallic structures in the immediate vicinity of a rooftop antenna produce multipath interference, pattern distortion, and increased ground losses that substantially degrade NVIS skywave performance relative to a clear rural site. The elevated rural sites (Pobit Kamak, Gorna Malina, Momina Skala) offered unobstructed radiating horizons that a dense urban rooftop could not match.

Second, and providing direct physical evidence, the support pillars of the mast structure formerly visible at the Slaveykov Square rooftop were too short to achieve the minimum antenna suspension height required for effective NVIS propagation. As established in Section 2 and corroborated by the shadow-comparison measurement at Pobit Kamak (Section 3), NVIS operation at the documented Bulgarian number station frequencies (4.74 MHz to 6.675 MHz) requires an antenna height of at least 11 m and ideally 16 m to 20 m above the supporting surface. The rooftop pillars at Slaveykov Square fell materially below this threshold. This was not a constraint for a ground-wave jammer, whose antenna orientation and height requirements are entirely different (Section 3.5), but it constituted a decisive objection to any NVIS skywave application. The mast height was thus positive physical evidence that the installation had been dimensioned for ground-wave operation from the outset, and was never intended for skywave propagation.

Third, the operational target of local ground-wave jammers in Sofia was *Radio Free Europe* (RFE) [1, 19], not Radio Liberty (RL). This distinction is important and is often elided in general accounts of Cold War jamming. Radio Liberty broadcast primarily in Russian and the languages of the Soviet nationalities, and was directed at audiences within the USSR. Its reception in Bulgaria was poor for two independent reasons. Geographically, Bulgaria lay at the periphery of Radio Liberty's intended coverage arc, and the signal levels reaching Sofia were substantially lower than at the intended reception areas in Russia and Ukraine. More significantly, the Soviet Union operated high-power skywave jamming transmitters in Western Siberia specifically tasked with jamming Radio Liberty on bearings towards Western Europe; the back-scatter and wide-angle radiation from these Siberian installations produced a considerable jamming effect even within Bulgaria itself, rendering local Bulgarian ground-wave supplementation of Radio Liberty jamming largely superfluous. Finally, and most practically: even though Russian-language instruction was formally compulsory in Bulgarian schools throughout the communist period, the proportion of the Bulgarian population with sufficient Russian-language proficiency to follow Radio Liberty's programming was in practice limited. Jamming Radio Liberty with ground-wave transmitters across Sofia would therefore have suppressed a signal that comparatively few Sofia residents could have understood in the first place, making such an operational commitment a poor use of scarce jamming resources. Radio Free Europe, by contrast, broadcast in Bulgarian and was directly intelligible to the entire population; its ground-wave suppression in Sofia and other Bulgarian cities was an operational priority of evident and immediate value.

The Pleikys survey of Soviet jamming architecture [1] explicitly documents that local jamming stations of 1 kW to 20 kW were used for ground-wave suppression of Western

broadcasts within city limits, to a radius of approximately 30 km, using VGDSh-type antennas mounted at low height. Georgiev [19] further confirms that the Bulgarian jamming infrastructure was organised on a dual-tier model: high-power skywave transmitters at Kostinbrod, Padarsko, and Stolnik covered large territories via ionospheric propagation, whilst short-range local stations suppressed RFE ground-wave reception in cities. The Slaveykov Square installation fitted structurally, physically, and geographically into this second, local RFE-jammer tier.

It should be noted that the Slaveykov Square site was unlikely to have been the only local ground-wave jamming installation in Sofia. The scale of the documented Soviet jamming effort, and the general practice of deploying multiple low-power stations within a city to achieve adequate ground-wave coverage across its full extent, suggests that additional such sites existed elsewhere in the capital. Their locations are not established from currently available open-source evidence, and since sites of this class were operationally unsuitable for number station transmissions on the grounds set out above, they are not investigated further in this study.

Accordingly, although the Slaveykov Square rooftop formerly carried antenna infrastructure of the same general type as the rural number station candidates, it was not a plausible number station transmitter. Its operational role was most probably local suppression of RFE ground-wave signals within Sofia, a function entirely consistent with its urban central location, its demonstrably short mast pillars, and the documented organisation of the Bulgarian jamming network. It is included here as a *negative example* that illustrates how VGDSh-type antenna infrastructure alone is an insufficient discriminant between number station and jamming functions: operational context, site geometry, propagation environment, and physical antenna dimensions are all necessary criteria.

3.5 Dual NVIS and ground-wave jamming use at the rural candidate sites: physical constraints

A further operational question merits direct treatment: whether any of the three primary rural candidate sites—Pobit Kamak, Gorna Malina, or Momina Skala—could have served *both* as a number station transmitter (NVIS skywave) *and* as a ground-wave jammer, using the same antenna installation. Simultaneous dual use is physically impossible, and sequential switching between the two functions requires a non-trivial antenna modification that is unlikely to have been routinely applied.

The fundamental incompatibility of NVIS and ground-wave polarisation

NVIS skywave propagation is maximised by a *horizontally polarised* antenna suspended at low height (typically $\lambda/4$ to $\lambda/2$), which directs the bulk of radiated energy upward at steep elevation angles towards the ionosphere. HF surface-wave (ground-wave) propagation, by contrast, is most efficient with *vertically polarised* antennas: the surface wave

is a transverse magnetic (TM) wave whose electric field is oriented perpendicular to the ground, and horizontally polarised sources produce a surface-wave component that attenuates extremely rapidly with distance [11]. A dipole or quadrant antenna installed in its standard horizontal orientation is therefore inherently poorly suited to ground-wave jamming; its surface-wave radiation is negligible compared with a vertical antenna of equivalent power.

The practical consequence is straightforward: a VGDSh or quadrant installation optimised for NVIS—horizontal elements at 16 m to 20 m height, as observed at Pobit Kamak—cannot simultaneously function as an effective ground-wave jammer in the HF band. The two roles impose mutually exclusive antenna geometries.

Physical requirements for sequential mode switching

Soviet-era engineering and amateur radio accounts document that the VGDSh was deployed in a ground-wave jamming role with the antenna oriented "vertically or at an angle" rather than in the standard horizontal configuration [1]. It must be noted, however, that this characterisation is based on a photograph caption in the Pleikys source and is not accompanied by detailed engineering data on the mounting arrangement; the precise tilt angle and feed-point adaptation required for efficient ground-wave radiation from a VGDSh element are not specified in any publicly available document known to the authors. Nonetheless, the electromagnetic principle is clear: the radiating element must be reoriented towards the vertical to produce effective surface-wave propagation.

Switching the same physical antenna between horizontal (NVIS) and vertical (ground-wave jammer) orientations at a fixed mast installation is not achievable by a simple electrical switch. The element geometry—the spatial orientation of the wire or cage conductors relative to the ground plane—is a mechanical property of the installation, not an electrical parameter that can be adjusted from the transmitter room. For a fixed-mast VGDSh or quadrant, transitioning between NVIS and ground-wave operation would in practice require:

1. Physical lowering of the antenna element and remounting it in a different orientation on the support mast, with corresponding re-rigging of guy wires and suspension points—an operation taking hours rather than minutes.
2. Replacement or modification of the impedance-matching network (balun, delta match, or shunting element), since the feed-point impedance changes substantially when a half-wave dipole transitions from horizontal to vertical orientation above a real ground plane.
3. Re-tuning of the transmitter's output network to match the revised antenna impedance.

For broadcast and jamming engineering practice, the standard solution was not to retune a

single antenna but to operate dedicated antennas for each function—a principle confirmed by Georgiev's account of the Padarsko site, where the jamming transmitter "Thunder" used its own control room and, by implication, its own antenna assets separate from the main broadcast infrastructure [19].

The quadrant antenna presents the same constraint as the VGDSh. The quadrant's two horizontal arms, suspended in a right-angled plan configuration from three mast points, cannot be reoriented to the vertical without dismantling and reconstructing the entire installation. No switching device within the transmitter building could achieve this reorientation; the mechanics of the antenna structure preclude it.

Conclusion: separate antenna assets for separate functions

The available evidence strongly supports the conclusion that NVIS skywave and ground-wave jamming functions were *not* performed by a single switchable antenna installation at the same site, but rather by separate, purpose-built antenna assets—whether at separate sites (the dual-tier model documented by Pleikys [1]) or within the same site perimeter using physically distinct antenna structures (as at Padarsko [19]).

This conclusion has direct implications for the assessment of the rural candidate sites. If Pobit Kamak, Gorna Malina, or Momina Skala were used for NVIS number station transmissions—which this study considers technically plausible—then any ground-wave jamming role at the same site would have required a separate, vertically oriented antenna installation alongside the horizontal NVIS structure. Whether such a secondary installation existed at these sites cannot be determined from available open-source evidence. The satellite imagery and photographic record reviewed for this study shows the horizontal NVIS-type mast structures; no additional vertical-polarisation elements have been identified at these locations, which is consistent with—though not conclusive proof of—an exclusively NVIS function at the rural candidate sites.

3.6 Kostinbrod, Padarsko, and Stolnik: the Bulgarian high-power network

A note on dual-use infrastructure

Before addressing Kostinbrod specifically, it is necessary to establish the correct analytical framework for Bulgarian shortwave infrastructure as a whole. Throughout the Soviet Bloc, high-power shortwave transmitter sites routinely served *dual purposes*: civil international broadcasting and electronic countermeasures (jamming), with the operational role at any given moment depending on the time of day, ionospheric conditions, frequency assignments, and political directives. This was not exceptional practice but standard Warsaw Pact doctrine. The same transmitter and, in many cases, the same antenna could be switched between a Bulgarian National Radio (BNR) programme relay and a jamming signal targeted at Western broadcasters, often within the same broadcast day.

Pleikys [1] documents the overall Soviet jamming architecture that Bulgaria participated in: thirteen long-distance skywave jamming centres with over 100 high-power transmitters (50 kW to 500 kW) covered large territories at distances of 500–3000 km using curtain array and rhombic antennas, whilst local ground-wave stations of 1–20 kW covered cities to approximately 30 km radius. By 1986, local jamming stations were present in 81 Soviet cities. Cross-border jamming agreements between Moscow, Sofia, Prague, and East Berlin formed the basis of the cooperative network, with Bulgaria specifically assigned to jam certain RFE/RL, VOA, BBC, and Deutsche Welle language services under these arrangements.

This dual function is directly confirmed by primary archival and field research. Georgiev's doctoral dissertation [19], based on field research at the abandoned Padarsko transmission station in May 2022 and on declassified documents at the Bulgarian Central State Archive (TsDA), establishes that the Padarsko site was explicitly and simultaneously used for both jamming and international radio transmission of Bulgarian programmes abroad. Georgiev's interlocutor, former station technician Hristo Hristev, confirmed that a separate control room directed a local jamming transmitter called "Thunder" while the main facilities operated BNR international services from the same perimeter. Declassified Bulgarian instructions from 1975 for the "organisation and exploitation of the means for radio defense," preserved in TsDA fond 308, explicitly describe the Bulgarian radio defence system as a sub-system of the joint Bulgarian–Soviet radio defence network, with Bulgaria's facilities covering part of Soviet territory whilst Soviet transmitters in the USSR covered Bulgaria's assigned jamming zones [19].

Furthermore, Georgiev documents that in the 1970s the eight most powerful jamming transmitters of 80 kW installed in Bulgaria were ordered and funded by the Soviet Union specifically to cover Soviet territory. A 1974 Ministry of Information report proposed a further 30 transmitters of 100 kW to be installed in three Soviet radio centres at distances of 1000, 2000, and 4000 km from Bulgaria. Engineers at the time explicitly acknowledged that transmission power alone was insufficient and that natural propagation factors—including the day/night cycle and seasonal variations in shortwave propagation—caused effectiveness to "drop dramatically" during certain periods [19]. Published Radio Bulgaria transmission schedules [20] confirm that Kostinbrod carried regular BNR shortwave services in Bulgarian, Russian, German, and other languages alongside its jamming function, while the country-data record for Bulgaria [21] explicitly lists Kostinbrod, Stolnik, and Plovdiv (Padarsko) as the principal foreign-language shortwave transmission sites.

Kostinbrod (42.809°**N,** 23.184°**E)**

Approximately 20 km north-west of Sofia, Kostinbrod is the largest and best-documented of the Sofia-area high-power installations. Published technical records [14] confirm Soviet-supplied transmitters installed between 1979 and 1982:

4× 50 kW Soviet PKM-50 transmitters; 2× 100 kW Soviet KV-100 transmitters; 1× 250 kW Czechoslovak PKV-250 transmitter; 1× 15 kW Soviet Molnia 2M transmitter.

The site carried Radio Bulgaria programmes in Russian, German, French, and Bulgarian, with transmissions on 7400 kHz beamed at 30° azimuth (towards the Soviet Union) at 100 kW [20]. The same infrastructure, at the same bearing and on the same or adjacent frequencies, served as a jamming platform when directed by the coordinated Warsaw Pact electronic countermeasures schedule.

Padarsko (near Plovdiv, 42.23°N, 24.52°E) and Stolnik (42.42°N, 23.35°E)

The Padarsko site, on the Thracian Plain near Plovdiv, is the best-documented example of Bulgarian dual-use shortwave infrastructure. It housed 250 kW and 500 kW Soviet PKV-series transmitters [14], with towers reaching 165 m in height [19]. Georgiev's first-hand account of the abandoned facility confirms that the jamming and broadcasting functions occupied physically separate but immediately adjacent control rooms within the same perimeter [19], consistent with the operational requirement for independent scheduling of the two activities whilst sharing common antenna and transmission infrastructure. After 1989 the site was repurposed entirely for Radio Bulgaria programme relays until the cessation of all Bulgarian shortwave services in 2012, when it was systematically demolished [19, 22]. The Stolnik site, 30 km east of Sofia, carried 100 kW and 15 kW transmitters and similarly served both civil broadcasting and countermeasures functions [14, 21].

The geometry of jamming: Radio Liberty at Platja de Pals

The directional logic of shortwave jamming is essential to understanding why Bulgarian sites were valuable to the Warsaw Pact electronic warfare programme. From 1959 to 2001, Radio Liberty's principal shortwave transmitter was located at *Platja de Pals* on Spain's Costa Brava [23, 24], at coordinates 41°59′0″N, 3°12′0″E—approximately 2,900 km from Moscow. The site was selected by Radio Liberty's chief engineer, Colonel S.Y. McGiffert, specifically for its oceanic foreground, which provided a superior reflecting medium for shortwave signals and allowed single-hop ionospheric propagation to fall entirely within Soviet territory [25]. At its peak, Platja de Pals operated six transmitters of 250 kW each, fed into directional curtain arrays of thirteen towers up to 169 m tall, with a combined effective radiated power that Soviet jamming assets found uniquely difficult to suppress [26].

Table 4 reveals the key geometric relationship. Radio Liberty's signal from Pals arrived at Moscow from a bearing of approximately 253° (west-southwest). The Bulgarian jamming transmitters, radiating north-northeastward at 28°–31°, delivered their signals to Moscow from the south-southwest (208°–211°)— a difference of approximately 42° from

Table 4: Great-circle bearings from Platja de Pals (Radio Liberty) and from Bulgarian jamming sites to principal Soviet target cities, illustrating the directional geometry of the jamming contest.

Site	**Moscow (°T)**	**Leningrad (°T)**	**Kyiv (°T)**	**Distance to Moscow (km)**
Platja de Pals (Spain)	46.3	33.5	56.3	2902
Kostinbrod (Bulgaria)	30.7	11.8	30.8	1772
Padarsko (Bulgaria)	27.6	9.4	24.6	1775
Stolnik (Bulgaria)	29.8	11.3	29.1	1803

the Pals arrival bearing. This angular separation matters for *directional* jamming strategies (where the receiving antenna is steered towards the jammed signal) but is largely irrelevant for the dominant Soviet jamming approach: *zone jamming*, in which powerful transmitters saturate the medium-wave and shortwave spectrum within the Soviet Union itself, regardless of the direction from which the Western signals arrive. Under this doctrine, a Bulgarian transmitter beaming high-power interference at the frequencies used by Radio Liberty contributed to the total noise level experienced by Soviet listeners, regardless of its angular relationship to the Pals signal. The closer proximity of Bulgarian sites to Soviet territory (Kostinbrod to Moscow: 1,772 km, versus Pals to Moscow: 2,902 km) also conferred a path-loss advantage of approximately 4 dB, making Bulgarian transmissions proportionally more effective per kilowatt for zone jamming than equivalent-power stations in Western Siberia.

The Bulgarian sites thus served a recognised role in the coordinated Warsaw Pact jamming apparatus—a "barter" arrangement within the socialist broadcasting infrastructure, whereby Bulgaria contributed jamming capacity directed against Radio Liberty and Radio Free Europe in exchange for Soviet technical assistance (the PKM-50, KV-100, and PKV-250 transmitters were all Soviet or Soviet-bloc supplied) and scheduling coordination through the OIRT (Organisation Internationale de Radiodiffusion et Télévision), the Eastern Bloc counterpart to the EBU.

The central caveat: absence of official disclosure

Before proceeding to any assessment of the high-power sites in relation to number stations, it is essential to acknowledge a fundamental limitation that applies to *all* sites considered in this study: the Bulgarian Government has never published any official information confirming or denying the operation of number stations from Bulgarian territory. This

stands in direct contrast to the Czech Republic, whose Office for Foreign Relations and Information (ÚZSI) has acknowledged the use of numbers stations, and to Poland, where the Institute of National Remembrance (IPN) has released documentary evidence of number station operations. No equivalent Bulgarian disclosure exists. All conclusions in this study are therefore probabilistic and inferential, not documentary.

Signal strength evidence and what it does, and does not, tell us

The monitoring records for S02 and E01—the two stations most consistently attributed to Bulgaria—describe signals that were receivable but not particularly strong at typical monitoring locations in Western Europe. No ENIGMA newsletter or systematic monitoring log records either station as a high-power transmission. This is consistent with the 5 W to 25 W operational power range derived in Section 4.4, and is *inconsistent* with the hundreds of kilowatts available at Kostinbrod or Padarsko. Two interpretations are, however, possible:

1. The transmissions were genuinely low-power, originating from one of the smaller candidate sites (Pobit Kamak, Gorna Malina, Momina Skala) using modest, purpose-built transmitters. This is the most straightforward interpretation and is operationally consistent with number station doctrine.

2. The transmissions may have originated from a high-power site such as Kostinbrod, but the monitoring records were made at locations far from the intended coverage zone. A signal from Kostinbrod at 250 kW beamed north-north-east towards the Soviet Union would appear weak at a monitoring receiver located to the north-west (in the United Kingdom, the Netherlands, or Germany), which lies *off the back of the beam*. In such geometry, the received signal level could be consistent with the observed moderate-to-weak reports even from a high-power transmitter.

Crucially, no monitoring record of *high-power* Bulgarian number station transmissions exists either. The absence of strong-signal reports neither confirms nor rules out a high-power origin; it is equally consistent with both a genuinely low-power source and a high-power directional source monitored from outside its coverage arc. The available signal intelligence record is therefore ambiguous on this point and cannot be used to definitively exclude any site.

Near-field emissions and local witness accounts

A further consideration is the phenomenon of near-field and parasitic emissions from high-power transmitter sites. Residents living near Kostinbrod, Padarsko, and Stolnik during the Cold War era have reported receiving strong, unusual shortwave signals on domestic receivers in the immediate vicinity of these sites—sometimes on frequencies not

listed in any official broadcasting schedule. Such reports, whilst anecdotal, are physically explicable by several mechanisms well known to transmitter engineers:

Direct-path ground-wave and near-field radiation. At distances of a few kilometres from the transmitter, the antenna's near field and ground-wave component may deliver substantial signal strength to receivers within line of sight of the antenna structure, regardless of the main beam elevation angle. NVIS and high-angle antennas—including the quadrant—radiate the majority of their energy skyward, but residual near-horizontal components at ground level remain detectable in the vicinity of the installation.

Harmonic and spurious emissions. High-power transmitters, particularly older Soviet-era valve designs, generate harmonic and intermodulation products that may appear at integer multiples or combination frequencies of the fundamental. A 100 kW transmitter on 7 MHz may produce a second harmonic at 14 MHz at 100 W to 500 W effective radiated power—entirely sufficient for local reception without appearing in any official schedule.

Feeder radiation. Open-wire feeders, imperfectly balanced coaxial runs, and unshielded balun transformers can re-radiate a fraction of the transmitted power as an unintentional ground-level omnidirectional source. At high power levels, even a −40 dB leakage fraction yields milliwatts to watts of stray radiation—more than sufficient for a local receiver.

These mechanisms mean that unusual transmissions heard at close range near any of the documented sites cannot reliably be attributed to intentional clandestine broadcasts; they may equally represent incidental artefacts of normal transmitter operation. Equally, however, they demonstrate that a number station transmission *could* have been operated from such a site without being distinguishable as a distinct signal by local observers.

Technical capability of all sites

Reconsidering the full picture in the light of these constraints, this study revises its site assessment as follows. All six primary sites in Table 3 (upper group)—including Kostinbrod, Padarsko, and Stolnik—must be regarded as *technically capable* of supporting number station operations, subject to the following qualifications:

The three primary candidate sites (Pobit Kamak, Gorna Malina, Momina Skala) remain the *most operationally plausible* for number station use, on grounds of power economy, infrastructure simplicity, and low observability. They require no adaptation of civil or jamming infrastructure, no operational cover story, and no high-power equipment.

The three high-power sites (Kostinbrod, Padarsko, Stolnik), despite their scale and dual-use function, cannot be categorically excluded. The dual-use character of all Warsaw

Pact broadcast infrastructure means that any of these sites could, at given hours or on specific frequencies, have operated a low-observable narrowband transmission alongside their primary schedule, or could have used their infrastructure to support a separate, low-power transmitter co-located within the same perimeter. The absence of Bulgarian official disclosure makes it impossible to confirm or deny this. The weak signal records for S02 and E01 are more naturally consistent with a modest dedicated transmitter, but the monitoring geometry cannot be established with certainty.

The conclusion of this study is that the present study establishes *technical feasibility* across all sites and *operational plausibility* at the three primary candidate sites, but falls short of attribution—as must any study conducted without access to the relevant Bulgarian State Security archives.

3.7 Additional Bulgarian transmitter sites considered and excluded

A number of additional Bulgarian shortwave transmitter sites have come to the authors' attention through open-source research, satellite imagery, and monitoring community records. Each was examined against the criteria developed in this study—the presence of VGDSh-type antennas, a power profile consistent with the low-power characteristics of the reported number station signals, proximity to Sofia as the presumed point of message origination, and the absence of disqualifying features such as dominant jamming infrastructure or impractically long relay requirements. In every case examined below, one or more of these criteria is not met, and the site is accordingly assessed as an implausible candidate for number station transmissions. The sites are listed in the lower group of Table 3 and are treated here individually.

Kozarevets (43°7′40.5″**N,** 25°49′5.6″**E**)

This site, located in north-central Bulgaria well to the east of the Danube plain, is equipped with both a VGDSh installation and a curtain array antenna. However, its distance from Sofia is substantial, making the logistics of encrypted message delivery to the transmitter highly problematic: any operational link between a Sofia headquarters and this site would require either a long leased landline or an intermediate relay arrangement, both of which introduce security risk and signal degradation. The most plausible assessed function of Kozarevets is jamming, for which its location and antenna complement are better suited. It is excluded as a number station candidate on logistical grounds.

Stolnik (42°42′21.9″**N,** 23°36′35.1″**E**)

Stolnik is equipped with a high-power curtain array but no VGDSh installation has been identified at this location. The transmitter power available at the site is very high and the site has been associated with jamming operations. Both the absence of a VGDSh-type

antenna and the high power profile are inconsistent with the low-power characteristics of the reported Bulgarian number station signals. Stolnik is excluded.

Kostinbrod (42°48′39.1″**N,** 23°11′0.6″**E**)

The Kostinbrod site, already discussed in detail in Section 3.6, presents a VGDSh installation alongside curtain arrays for shortwave and quadrant antenna structures. However, the transmitter powers available—ranging from 50 kW to 250 kW—far exceed the power profile consistent with the observed signal characteristics of S02 and E01, and the site has been documented as a jamming platform. Whilst a separate low-power co-located transmitter cannot be categorically excluded (as noted in Section 3.6), Kostinbrod is not assessed as a primary number station site on power profile grounds.

Varna (43°8′50.5″**N,** 27°52′42.4″**E**)

A curtain array antenna is present at the Varna coastal site; its physical dimensions— in particular the size and height of the antenna structure—imply a design frequency above 10 MHz, which falls outside the documented operating range of S02 and E01 (4.74 MHz to 6.675 MHz). No VGDSh antenna has been identified or reported at this location. From a propagation standpoint, a coastal site on the Black Sea is not inherently disqualifying, but the distance from Sofia—where, on the hypothesis of this study, the encrypted messages were generated—is considerable. A secure message delivery chain from Sofia to Varna would require either a long leased line or a relay arrangement, neither of which is consistent with the operational simplicity expected of a low-profile number station facility. Varna is assessed as a possible but impractical number station site and is excluded on logistical grounds.

Grivitsa (43°24′18.1″**N,** 24°45′27.2″**E**)

Grivitsa, located on the Danube plain in north-central Bulgaria, is assessed as a jamming facility. Curtain array antennas consistent with a jamming role are present, and a VGDSh installation has been reported. However, the antenna mounting height is low, consistent with ground-wave rather than skywave operation. The assessed primary function of this site is ground-wave jamming providing coverage over Pleven and neighbouring cities. It is excluded as a number station candidate on the basis of its antenna configuration and power profile.

Kocherinovo (42°2′48.1″**N,** 23°2′55.2″**E**)

A curtain array antenna has been reported at Kocherinovo, and VGDSh antennas have been identified at the site in past imagery, alongside documented jamming activity. The

VGDSh antennas appear to be mounted low, consistent with ground-wave operation rather than NVIS skywave. The site lies south of Sofia at a distance inconsistent with the logistical simplicity of a Sofia-proximate number station. Its assessed primary function is ground-wave jamming covering Blagoevgrad, Dupnitsa, and Petrich. It is excluded as a number station candidate.

Mogila (42°23′38.8″N, 25°42′15.7″E)

VGDSh antennas have been reported at Mogila in the past, and jamming activity has been documented at this site. As at Grivitsa and Kocherinovo, the VGDSh installations appear to be mounted at low height, consistent with ground-wave rather than NVIS skywave radiation. The distance from Sofia and the power profile are both inconsistent with the characteristics of the reported number station signals. The assessed primary function is ground-wave jamming providing coverage over Stara Zagora, Nova Zagora, and Yambol. It is excluded as a number station candidate.

Stamboliyski (42°8′24.6″N, 24°32′22.3″E)

VGDSh antennas have been reported at Stamboliyski in the past, and jamming activity has been documented. As with the other ground-wave jamming sites in this group, the VGDSh installations are assessed as low-mounted, and the power profile is inconsistent with the low-power characteristics of the reported number station signals. The assessed primary function is ground-wave jamming providing coverage over Plovdiv and adjacent cities to the south-west. It is excluded as a number station candidate.

Summary

Of the eight additional sites examined in this subsection, none meets the combined criteria of VGDSh presence, low-power consistency, Sofia proximity, and operational logistical simplicity that characterise the primary candidate sites (Pobit Kamak, Gorna Malina, Momina Skala). The dominant pattern among the excluded sites is assignment to ground-wave jamming functions—characterised by low-mounted VGDSh antennas covering city-scale areas—which is operationally and technically distinct from the NVIS skywave role required for number station transmissions to distant agents. Varna represents a partial exception in that a curtain array is present and its coastal location is not physically disqualifying, but the relay distance from Sofia and the mismatch between the observed antenna design frequency and the documented number station operating frequencies both argue against it. The overall inventory of known Bulgarian shortwave transmitter sites therefore does not produce any additional plausible number station candidates beyond the three primary sites and, with greater uncertainty, the high-power dual-use sites (Kostinbrod, Padarsko, Stolnik) already assessed in Section 3.6.

4 Propagation analysis and coverage assessment

4.1 Frequency selection and propagation mode

For the range of target distances under consideration (476 km to 1,603 km), the principal propagation mechanism is single-hop ionospheric skywave, predominantly via the F2 layer at night and the F1 or combined F-layer during daylight hours. For distances up to approximately 1,000 km, near-vertical incidence skywave (NVIS) represents the dominant mode; for greater distances, oblique skywave at elevation angles of 15° to 35° becomes important.

The following frequency–distance guidance applies under typical mid-latitude ionospheric conditions:

Table 5: Recommended operating frequencies for target distances from the Sofia region.

Distance range (km)	Night (MHz)	Day (MHz)
400 to 800	7–9	9–11
800 to 1,300	7–11	11–15
1,300 to 1,600	9–13	13–17

All of the listed frequencies lie within the operational range of the HQ commercial quadrant (5.9 MHz to 26.1 MHz) and within the usable range of the single-wire cut-delta quadrant with appropriate scaling of arm dimensions.

4.2 Great-circle distances and bearings from each site

Tables 6, 7, and 8 present the geodetic great-circle distances and true bearings from each transmitter site to the principal cities of each target country. Distances flagged with † exceed the published maximum coverage radius of the quadrant antenna at its rated maximum power of 500 kW; these are discussed separately in Section 4.5.

Table 6: Great-circle distances and bearings: Pobit Kamak (Vakarel).

City	Country	Distance (km)	Bearing (°T)
Vienna	Austria	844	320.3
Salzburg	Austria	1011	308.7
Munich	Germany	1124	307.4
Berlin	Germany	1343†	328.9
Frankfurt	Germany	1416†	311.4
Milan	Italy	1197	290.4

(continued)

City	Country	Distance (km)	Bearing (°T)
Rome	Italy	920	269.0
Zurich	Switzerland	1299	299.4
Bern	Switzerland	1364†	296.4
Ankara	Turkey	825	108.0
Istanbul	Turkey	476	109.8
Athens	Greece	512	179.1
Nicosia	Cyprus	1177	131.1
Jerusalem	Israel	1577†	135.9
Tel Aviv	Israel	1525†	136.3

Table 7: Great-circle distances and bearings: Gorna Malina.

City	Country	Distance (km)	Bearing (°T)
Vienna	Austria	836	319.6
Salzburg	Austria	1006	308.0
Munich	Germany	1119	306.8
Berlin	Germany	1334†	328.5
Frankfurt	Germany	1411†	310.9
Milan	Italy	1196	289.9
Rome	Italy	923	268.3
Zurich	Switzerland	1296	298.9
Bern	Switzerland	1362†	295.9
Ankara	Turkey	825	108.9
Istanbul	Turkey	477	111.4
Athens	Greece	524	179.6
Nicosia	Cyprus	1182	131.7
Jerusalem	Israel	1584†	136.3
Tel Aviv	Israel	1531†	136.8

Table 8: Great-circle distances and bearings: Momina Skala (Vitosha).

City	Country	Distance (km)	Bearing (°T)
Vienna	Austria	820	321.6
Salzburg	Austria	983	309.4
Munich	Germany	1096	308.0
Berlin	Germany	1322†	329.7
Frankfurt	Germany	1389†	311.8
Milan	Italy	1165	290.5
Rome	Italy	888	268.4
Zurich	Switzerland	1269	299.6
Bern	Switzerland	1333†	296.5
Ankara	Turkey	857	107.3
Istanbul	Turkey	508	108.8
Athens	Greece	518	175.3
Nicosia	Cyprus	1204	130.0
Jerusalem	Israel	1603†	134.9
Tel Aviv	Israel	1550†	135.3

† Exceeds the published 1,300 km maximum coverage radius for the HQ quadrant at 500 kW; see Section 4.5.

4.3 Geometric analysis: bearing arcs

Inspection of the bearing data reveals a particularly convenient geometric property of all three sites relative to the target distribution. The north-western targets (Austria, Germany, Switzerland, northern Italy) lie within a bearing arc of approximately 290° to 332°, whilst the south-eastern targets (Turkey, Greece, Cyprus, Israel) lie within a bearing arc of 107° to 180°. These two arcs are effectively diametrically opposed.

An omnidirectional antenna such as the quadrant therefore simultaneously illuminates *both* arcs from a single fixed installation, with no requirement for phased arrays, beam steering, or multiple directional curtain antennas. This is of substantial operational significance: a clandestine facility equipped with a quadrant antenna could address agents in Vienna, Rome, Istanbul, and Athens simultaneously from a single transmission, on a single frequency and schedule, without any change in antenna orientation or transmitter configuration.

4.4 RF link budget

The received signal power P_r at an agent's receiver may be expressed via the Friis transmission equation adapted for ionospheric skywave propagation:

$$P_r = P_t + G_t - L_p - L_a - L_f + G_r \tag{1}$$

where all quantities are in dBm or dB as appropriate, and:

P_t = transmitter output power (dBm),
G_t = transmitting antenna gain relative to isotropic (dBi),
L_p = ionospheric path loss (dB),
L_a = ionospheric absorption loss (dB),
L_f = fading margin (dB),
G_r = receiving antenna gain (dBi).

The correct performance criterion: intelligibility, not broadcast quality

A fundamental distinction must be drawn between the performance standard applicable to international broadcasting and that applicable to number station reception. A broadcast service must be reliably intelligible to a general population of listeners using consumer-grade receivers under varying conditions, demanding a signal-to-noise ratio (SNR) of 16 dB or more above the noise floor and a generous fading margin.

A number station, by contrast, operates to an entirely different standard. The receiving agent is a *trained individual*, listening at a *known time* on a *known frequency*, for a *known format*: slow, clearly enunciated, repeated five-figure groups. Speech intelligibility research and operational practice consistently show that digit recognition in a known format is achievable at SNR values as low as +3 dB to +6 dB above the noise floor—a threshold roughly 10 dB below that required for comfortable general broadcasting. High transmitter power is not an operational requirement; it is a liability. A powerful signal radiating omnidirectionally is readily detected, direction-found, and attributed. The correct engineering objective for a number station transmitter is the *minimum power sufficient to achieve digit intelligibility at the agent's location*, with a modest fading margin only.

The governing noise source: external HF atmospheric and man-made noise

At the documented Bulgarian station frequencies (4.74 MHz to 6.675 MHz), the noise environment at a receiving location in Central or Southern Europe is not limited by the thermal noise floor of the receiver but by *external* atmospheric and man-made HF

noise, as characterised by ITU-R Recommendation P.372 [11]. For a suburban or rural European location at these frequencies during nighttime hours, the external noise figure F_a is approximately 55 dB above the thermal reference (kTB). This overwhelms any reasonable receiver noise figure and sets the effective noise floor far above the thermal limit:

$$N_{\text{eff}} = kTB \cdot 10^{F_a/10} \tag{2}$$

For a narrowband AM receiver with a 3 kHz audio bandwidth (appropriate to number station voice), the effective noise floor is therefore approximately $-139 + 55 = -84$ dBm. This is the figure that governs minimum received signal requirements—not the receiver's own thermal noise floor.

Minimum power calculation

Table 9 presents the computed minimum transmitter power required to achieve digit intelligibility (SNR $\geq +6$ dB above the external noise floor, with a 10 dB fading margin) at each primary target, using the cut-delta quadrant (5.4 dBi) at the transmitter and a short random wire (1.5 dBi) at the receiving end—the most operationally conservative receiving antenna assumption, consistent with an agent using a few metres of wire in an apartment.

Table 9: Minimum transmitter power for number station digit intelligibility. External noise: ITU-R P.372 $F_a = 55$ dB (suburban Europe, nighttime). Narrowband AM, 3 kHz BW; SNR threshold +6 dB; fading margin 10 dB; $G_t = +5.4$ dBi (cut-delta quadrant); $G_r = +1.5$ dBi (short wire).

Target	**Dist. (km)**	**Path loss (dB)**	$P_{\min}$ **(W)**	**10 W margin (dB)**
Istanbul (4.74 MHz)	477	90	0.03	+25
Athens (6.675 MHz)	512	92	0.05	+23
Vienna (5.5 MHz)	820	101	0.39	+14
Vienna (6.675 MHz)	820	102	0.49	+13
Munich (6.675 MHz)	1097	108	1.95	+7
Nicosia (6.675 MHz)	1180	110	3.09	+5

The results are striking. For the closest targets (Istanbul, Athens), a transmitter power of tens of milliwatts is physically sufficient for intelligibility; a standard 10 W transmitter provides more than 23 dB of margin above the minimum. For the primary Central European target, Vienna at 820 km, the minimum power is approximately 500 mW, and a 10 W transmitter yields 13 dB of margin—amply robust against typical nighttime fading whilst

remaining entirely inconspicuous. Even at Munich (1,097 km) and Nicosia (1,180 km), transmitter powers of 5 W to 10 W exceed the intelligibility threshold by 4 dB to 8 dB.

These theoretical minimum power figures must, however, be qualified by an important operational constraint on the *receiving* end of the link. The $P_{\min}$ values in Table 9 are computed assuming a receiving antenna gain of +1.5 dBi, corresponding to a short random wire in a favourable outdoor location. In practice, achieving even this modest figure requires a reasonably positioned wire of several metres length with an unobstructed view of the sky—a luxury that a clandestine agent operating under cover in an urban environment typically could not afford. Field agents maintaining a low profile in a city flat would almost invariably use a compact portable receiver with a short built-in telescopic whip or a few metres of wire strung inconspicuously around the room, presenting a receiving antenna gain that may be 5 dB to 10 dB below the assumed figure. In a dense urban environment, additional attenuation from surrounding buildings, reinforced concrete structures, and local man-made radio-frequency noise would further degrade the effective received signal level.

The practical consequence is that the theoretical minimum transmitter powers shown in Table 9—tens of milliwatts for Istanbul, a few hundred milliwatts for Vienna—whilst physically achievable under idealised link conditions, do not represent operationally realistic minima for agent communications. A receiving installation constrained to a concealed urban location with a modest antenna may require 10 dB to 15 dB more transmitter power than the theoretical minimum to achieve the same digit intelligibility. This correction brings the practically reliable minimum transmitter power for the primary target arc into the range of 5 W to 50 W—consistent with, and providing an independent justification for, the standard Warsaw Pact fixed-installation HF transmitter powers of 500 W to 1 kW discussed below.

Table 10 further illustrates the relationship between transmitter power and reception quality at the Vienna benchmark distance.

The minimum power consistent with reliable intelligibility across the primary target arc is therefore 5 W to 25 W. In practice, however, standard fixed-installation HF transmitters available to Warsaw Pact military and state security services during the Cold War were typically rated at 500 W to 1 kW carrier power. Equipment in this class—such as the Soviet R-140, or comparable fixed-station transmitters of East European manufacture—was the normal complement of any permanent military communications post and represented no unusual procurement requirement. Operating such a transmitter at its rated power on the Sofia–Vienna path (820 km, 6.675 MHz, nighttime) provides a link margin of approximately +43 dB above the intelligibility threshold—far in excess of any operational requirement, but entirely consistent with the standard practice of using rated equipment at its designed power level rather than operating it at artificially reduced output.

This apparent paradox—that the minimum necessary power is 5–25 W whilst the probable actual power was 500 W to 1 kW—has a straightforward operational explanation. An

Table 10: Reception quality as a function of transmitter power: Vienna (820 km), 6.675 MHz, nighttime. Minimum intelligibility power: ≈ 0.5 W.

Tx power	**Margin above $P_{\min}$**	**Assessment**
1 W	+3 dB	Marginal; copies on good nights
5 W	+10 dB	Reliable intelligibility most nights
10 W	+13 dB	Good; robust against moderate fading
25 W	+17 dB	Excellent; effective on virtually all nights
50 W	+20 dB	Unnecessary excess; no operational benefit
100 W	+23 dB	Broadcast-grade; operationally counterproductive

intelligence service does not procure a special low-power transmitter for a number station; it uses the standard fixed-installation equipment already present at the site, operated at its normal rated power. The consequence for signal monitoring is that the transmissions would have appeared as a moderately strong but not exceptionally powerful signal to monitoring receivers—consistent with the observed moderate signal strength records for S02 and E01 in the ENIGMA logs, and consistent with the known characteristics of Soviet-era fixed HF communications equipment. A 500 W to 1 kW transmitter feeding a VGDSh at these frequencies produces an effective radiated power entirely unremarkable against the background of routine military shortwave communications traffic, and leaves no site-revealing infrastructure signature of the kind associated with the high-power jamming and broadcasting facilities at Kostinbrod or Padarsko.

The critical distinction remains: 500 W to 1 kW from a compact fixed-station transmitter with a simple wire antenna is operationally invisible; 50 kW to 250 kW from a multi-stage valve transmitter with forced cooling and a large curtain array is not.

4.5 Targets beyond 1300 km: extended range

The published maximum coverage radius of the commercial HQ broadcast quadrant at 500 kW is 1,300 km [9]. This specification is, once again, a broadcast-grade figure applicable to mass audiences with unspecified receiver quality. For a dedicated agent receiver with a purpose-tuned antenna, and given the intelligibility-threshold criterion established above, the effective coverage of a 25 W narrowband AM transmission at 6.675 MHz extends

well beyond 1,300 km on favourable ionospheric nights. Berlin (1,322 km to 1,343 km) and Frankfurt (1,389 km to 1,416 km) fall within this extended range, as does Nicosia (1,180 km), which is already covered within the primary power budget of Table 9. For Israel (1,525 km to 1,603 km), a higher frequency (9 MHz to 11 MHz) or slightly higher power (50 W to 100 W) would be required to achieve a robust intelligibility margin under average conditions, but neither represents any departure from a low-observable transmitter installation.

The critical operational conclusion is that **no site-revealing infrastructure is required at any distance considered in this study**. Numbers station operations are inherently narrowband and intelligibility-limited, not bandwidth- or quality-limited. The entire operational requirement—from Istanbul to Munich to Nicosia—is met by a transmitter that could fit in a small suitcase and run from a standard 220 V domestic supply, with a quadrant antenna indistinguishable from a routine military communications wire installation.

5 Comparative site assessment

5.1 Scoring criteria

The three candidate sites are assessed against the following criteria, each on a notional scale relevant to Cold War clandestine operations:

1. Proximity to primary target bearing arc (NW, towards Central Europe);
2. Ground conductivity and topographic clearance for NVIS propagation;
3. Low observability (site concealment, plausible civilian cover);
4. Logistics and infrastructure access (road access, power supply);
5. Distance from Sofia (proximity to command and control).

5.2 Assessment summary

Gorna Malina presents the most favourable overall profile. Its position on the flat Sofia Plain provides the best ground conductivity for NVIS propagation, offers unobstructed horizons in all azimuths, and lies within 30 km of Sofia with good road access. The comparatively lower elevation (560 m) is not a disadvantage for NVIS-dominated propagation at 7 MHz to 9 MHz, where antenna height above ground in wavelengths is the governing parameter, not altitude above sea level per se.

Pobit Kamak (Vakarel) offers a modest topographic advantage to the north-west and benefits from elevated terrain. However, the south-easterly shift in position slightly increases bearings to Central European targets and marginally reduces coverage of the western Italian sector.

Momina Skala (Vitosha), despite its imposing elevation of 1,250 m, presents certain operational disadvantages. The Vitosha massif itself may introduce topographic shielding at low elevation angles to the south and east, and the site is more visible and accessible than a plain-based installation. However, the high elevation does benefit radiation at low takeoff angles in the north-westerly direction and would be particularly advantageous if a stacked cage quadrant—with its characteristic low-angle gain enhancement of 9.6 dBi at 17° elevation [8]—were employed for coverage of more distant targets.

6 Operational considerations and covertness

6.1 Antenna observability

The single-wire cut-delta quadrant, with arm lengths of approximately 14 m at 7.15 MHz, can be erected between three timber poles or between conveniently positioned trees and presents minimal visual signature. It requires no large lattice mast. Beaumont notes that the first proof-of-concept installation used three trees in a domestic garden. An intelligence service operating under the cover of a civilian shortwave relay station, an agricultural radio link, or a military communications post would have found this antenna unexceptional in appearance.

The Wells cage quadrant, whilst larger and more visually prominent, is identical in external appearance to a legitimate international broadcasting antenna and would attract no attention at a site already designated as a radio transmission facility.

6.2 Frequency agility and schedule discipline

Number station operations are characterised by strict frequency and schedule discipline: a fixed frequency and transmission time known only to the intended recipient and the originating service. The quadrant's operational bandwidth of approximately one octave (for the cage design) or a single amateur band segment (for the single-wire cut-delta) supports selective operation on a pre-assigned frequency without the need for real-time tuning or switching, reducing the number of operators and mechanical components required.

6.3 Direction-finding resistance: the role of the azimuth radiation pattern

A property of the quadrant antenna that has not previously been discussed in the context of clandestine radio operations, but which is of direct operational relevance, is its inherent resistance to direction-finding (DF). This resistance arises directly from the omnidirectional azimuth pattern that is the quadrant's defining characteristic, and it applies regardless of whether the monitoring organisation was the Cold War-era ENIGMA listening network, a national SIGINT service, or a military DF network.

The physical basis of direction-finding

Conventional shortwave DF receivers—whether rotating loop aerials, Adcock arrays, or aperture-synthesis Wullenweber installations (colloquially known as "elephant cage" arrays)—determine the bearing to a transmitter by exploiting the *angular variation* of the received signal amplitude as a function of azimuth. The fundamental parameter governing DF accuracy is the rate of change of antenna gain with azimuth, $\mathrm{d}G/\mathrm{d}\theta$, at the bearing of interest. For a directive antenna with a narrow main lobe, this derivative is large on the lobe flanks, producing a sharp and unambiguous bearing estimate. The Cramér–Rao

lower bound on bearing estimation error for a directive transmitting antenna with azimuth beamwidth $\theta_{3\,\mathrm{dB}}$ and received signal-to-noise ratio S (linear) is approximately:

$$\sigma_\theta \approx \frac{\theta_{3\,\mathrm{dB}}}{2\sqrt{2S}} \tag{3}$$

For a curtain array with $\theta_{3\,\mathrm{dB}} = 30°$ operating at $S = 20\,\mathrm{dB}$ ($S_{\mathrm{lin}} = 100$), Equation (3) yields $\sigma_\theta \approx 1.1°$. At this bearing precision, two DF stations separated by 500 km (e.g. Vienna and Munich) produce cross-bearing position uncertainties of approximately 15 km to 20 km at 900 km range—sufficient to resolve an individual transmitter site within the Sofia region.

The quadrant: near-zero azimuth gradient

The quadrant antenna presents an entirely different situation. As documented by Beaumont [8], the cut-delta quadrant at 7.15 MHz suspended at $5\lambda/12$ height exhibits an azimuth gain variation of only ± 0.9 dB at 35° elevation (as shown in the azimuth pattern plots of that report), whilst the commercial HQ broadcast quadrant is specified as omnidirectional [9]. A gain variation of ± 0.9 dB across the entire 360° azimuth corresponds to a gradient $\mathrm{d}G/\mathrm{d}\theta$ that is, for practical purposes, indistinguishable from zero at any bearing. In the limit of a truly omnidirectional pattern, $\mathrm{d}G/\mathrm{d}\theta = 0$ everywhere and Equation (3) becomes singular—the Cramér–Rao bound on bearing error is unbounded, meaning that a DF receiver exploiting only the amplitude variation of the received signal cannot extract a meaningful bearing estimate at all.

In practice, the near-omnidirectional character of the quadrant means that a rotating loop or Adcock DF receiver, which relies on finding a signal maximum or null as the antenna rotates, cannot form a well-defined null or peak in the azimuth response. The result is a broad, shallow azimuth variation from which a bearing can be estimated only with large uncertainty. Table 11 quantifies the cross-bearing position uncertainty for several representative transmitter antenna types, assuming a realistic Cold War-era DF bearing error.

At a realistic bearing uncertainty of 10° or greater for an omnidirectional source, the cross-bearing position fix at 900 km range has a cross-range uncertainty exceeding 160 km. This is larger than the entire Sofia region under study: the three primary candidate sites (Pobit Kamak, Gorna Malina, and Momina Skala) are all within 60 km of Sofia city centre and cannot be distinguished from one another—or even from Sofia itself—under these conditions. Importantly, this DF resistance applies equally to the VGDSh-2U (crossed-dipole) variant and the quadrant, both of which produce near-omnidirectional azimuth patterns. The single-element VGDSh offers somewhat better DF-ability due to its end-fire nulls, but even then, ionospheric multipath at the documented frequencies (4.74–6.675 kHz) broadens the effective bearing uncertainty well beyond the theoretical end-fire

Table 11: Direction-finding bearing error and position uncertainty at 900 km range as a function of transmitting antenna type. Two DF stations separated by 500 km, SNR = 20 dB.

Transmitting antenna	**Azimuth BW**	**Bearing error (σ_θ)**	**Cross-range uncertainty at 900 km**
Curtain array (HRS-4/4)	30°	$\approx 1°$	≈16 km
Rhombic	20°	$\approx 0.7°$	≈11 km
VGD / VGDSh (single dipole)	78°	$\approx 2.8°$	≈44 km
VGDSh-2U (crossed dipoles)	±5 % variation	$\gg 10°$	≫160 km
Quadrant (cut-delta / HQ)	±0.9 dB variation	$\gg 10°$	≫160 km

null geometry.

TDOA methods and their Cold War limitations

Time-difference-of-arrival (TDOA) techniques, which compare the phase or timing of a signal received at multiple geographically separated stations, are in principle independent of the transmitting antenna pattern and could resolve the bearing ambiguity of an omnidirectional source. However, effective TDOA-based geolocation during the Cold War period required simultaneous reception at three or more well-separated stations with synchronised clocks or a common timing reference, together with the computational infrastructure to cross-correlate wideband recordings. Such capabilities existed within national SIGINT agencies (particularly NSA and GCHQ), but the ENIGMA monitoring community and similar civilian shortwave listeners were entirely without them. Furthermore, TDOA accuracy for a narrowband, low-power AM transmission on an interband frequency is further limited by ionospheric multipath: the signal arrives at each receiving station via multiple ionospheric paths with slightly different delays, broadening the cross-correlation peak and degrading timing precision. This effect is most pronounced at the lower frequencies (4.74–6.675 kHz) documented for the Bulgarian number stations, where NVIS propagation produces multiple closely spaced ionospheric reflection paths.

Implication for location attribution

The combined effect of the near-omnidirectional radiation pattern and the interband frequency selection of S02 and E01 is that these transmissions were, from a DF perspective, maximally difficult to locate precisely. Even a well-equipped Cold War SIGINT service

using conventional bearing-finding equipment could at best determine that the transmitter was somewhere within a broad arc extending through Bulgaria and the surrounding region, without being able to distinguish between the candidate sites within the Sofia area or, indeed, between Sofia and other potential origins in the wider Balkan region. This is consistent with the ENIGMA community's attribution of these stations to Bulgaria as a country rather than to any specific transmitter site, and it constitutes an additional operational argument in favour of the quadrant antenna for this application beyond its propagation and power economy characteristics.

6.4 Power economy, covertness, and site observability

The link budget analysis of Section 4.4 establishes that the entire operational requirement of a number station serving the Sofia–Central Europe and Sofia–Eastern Mediterranean target arcs is met by a transmitter in the range of 5 W to 25 W. This is the most operationally significant finding of the present study.

A transmitter of this power class is entirely unremarkable. It occupies a volume comparable to a domestic audio amplifier, requires no forced-air cooling, draws less than 100 W from a standard 220 V domestic mains supply, and produces no externally detectable electromagnetic or thermal signature at distances exceeding a few tens of metres. It can be operated from a vehicle, a converted outbuilding, or a room in an otherwise unremarkable residential or administrative building. It produces no detectable radio-frequency interference to neighbouring equipment at distances beyond the immediate premises.

This is in direct contrast to the 500 kW transmitters of the Kostinbrod jamming facility, whose power supply infrastructure, cooling systems, and ground radial networks are visible from satellite imagery and whose broadband radio-frequency emission is detectable by monitoring services at intercontinental distances.

The key operational principle is that high power is not only unnecessary for number station use—it is actively counterproductive. A high-power transmission can be detected by signals intelligence (SIGINT) assets at long range, direction-found by triangulation, and used to localise the originating facility. A 10 W narrowband AM transmission on an interband utility frequency, by contrast, lies within the ambient HF noise environment of any monitoring receiver operating beyond approximately 500 km from the transmitter, whilst remaining entirely adequate for a trained agent at a known frequency and time.

6.5 Message origination, delivery to the transmitter site, and voice generation

A dimension of number station operation that has received less attention than the RF engineering and propagation questions is the chain by which an encrypted message originating at a headquarters was converted into an audible voice transmission at a remote transmitter site. This chain involves at least two distinct problems: the delivery of the message

text to the transmitter location, and the conversion of that text into a reproducible, intelligible voice output. Both problems admit several solutions, and the approach adopted by a given service reflects its technical resources, the available telecommunications infrastructure, and the security constraints of the period. In the case of the Bulgarian stations, the precise method remains unknown in the absence of primary archival evidence, but the principal variants can be identified and their relative merits assessed.

Delivery of the message text to the transmitter site

The entity responsible for operating number stations S02 and E01 is not established in the open record. Candidate organisations include the Bulgarian State Security (DS) and its foreign intelligence arm (PGU), military intelligence (RU), and military counter-intelligence (VKR), all of which operated agent networks during the Cold War period. In all scenarios, the message—an OTP-encrypted sequence of five-figure groups—would have been generated at the headquarters of the originating service in Sofia and needed to reach the transmitter site, which may have been 30 km or more from the city.

Three principal delivery mechanisms were technically feasible during the Cold War era:

1. **Dedicated landline (wire link).** A direct telephone or telegraph line between the headquarters and the transmitter site, carrying either a pre-recorded audio signal or real-time audio. Fixed military and state security sites in Bulgaria were routinely connected to dedicated, encrypted landline networks operated by the Directorate of Government Communications, providing secure channels for exactly this purpose. The principal disadvantage of a long wire link for audio is signal degradation over distance: analogue voice signals on copper pairs suffer from frequency-dependent attenuation and phase distortion, requiring repeater amplifiers and equalisation filters at intervals of tens of kilometres to maintain intelligible audio quality. For a 35 km link to Pobit Kamak, at least one repeater stage would have been required to preserve audio bandwidth adequate for speech.

2. **Voice synthesis machine at the transmitter site.** A speech generator device located physically at the transmitter building, operated by local support staff. The message text—delivered by courier or secure telex rather than as an audio signal—would be loaded into the device at the site, and the device would produce the voice output locally and feed it directly to the transmitter's audio input. This approach eliminates the audio-quality problem of long-distance landline transmission entirely, since only digital or coded data need traverse the link between headquarters and site; the voice synthesis occurs at the point of transmission. The East German *Gerät 32620 Stimme* [27] ("Voice," also known as the *Eiserne Frau* or Iron Lady) is a documented example of exactly this class of device: a compact digital speech generator developed by the Institut für Kosmosforschung of the DDR in 1982–83 for use by the *Ministerium für Staatssicherheit* (MfS/Stasi), accepted into service

in 1984, and subsequently supplied to the intelligence services of other Warsaw Pact states including the Soviet Union and Poland. The device accepted messages on 5-level punched paper tape, via keypad, or through a serial modem connection, and produced a digitised female voice output on a 600 Ω audio line, suitable for direct connection to a transmitter's microphone or audio input. The Cryptomuseum documentation confirms that the 32620 was designed to be positioned at or near the transmitter [27], consistent with the local synthesis model. Whether a Bulgarian-language speech module was ever produced for the 32620 is not confirmed in the open record.

3. **Voice synthesis at headquarters, transmitted over the wire link as data.** A variant of both approaches above: the synthesis machine is operated at the headquarters, and its audio output—or a digital encoding of it—is sent to the transmitter site over the landline. This offers the advantage of centralised control of the device, keeping sensitive equipment at headquarters rather than at a remote site staffed by technical personnel of potentially lower security clearance. The disadvantage is that transmitting audio over a long cable reintroduces the signal quality problems of the landline option above, unless the audio is pre-encoded digitally before transmission and decoded at the site—a more sophisticated arrangement than would have been typical of Bulgarian state security infrastructure in the 1960s to 1980s.

A fourth operational method, less elegant but entirely practical within the technical and security constraints of the period, deserves separate consideration: the encrypted message, rather than being transmitted as audio over the wire link, could be relayed from headquarters to the transmitter site over a *radio channel* itself—in Morse code or another digital encoding—and decoded by local support staff at the site, who would then enter the digit sequence into the voice synthesis machine or pre-recorded tape system. This approach requires trained operators at the transmitter site capable of receiving and decoding Morse, but eliminates any dependence on landline infrastructure and is entirely consistent with standard Warsaw Pact communications doctrine for dispersed military and intelligence facilities. It also has the significant operational advantage that no sensitive audio or plain-text material traverses any wire link that could be tapped; the over-the-air Morse transmission carries only ciphertext, and the voice output is generated locally without any external connection during the transmission.

Which of these methods was employed at the Bulgarian candidate sites cannot be determined from available open-source evidence, and the question may not be resolvable without access to DS or military intelligence operational archives.

Voice quality: the acoustic case for a female announcer

The use of a female voice for the digit announcements of both S02 and E01 is a deliberate and technically motivated choice, not an arbitrary one. Female speech has measurably

superior intelligibility characteristics relative to male speech under the specific degraded-channel conditions that characterise shortwave AM reception. The acoustic basis for this advantage operates through two related mechanisms.

First, female fundamental voice frequency (F_0) is substantially higher than male— typically 165 Hz to 255 Hz for women versus 85 Hz to 180 Hz for men—and the formant structure of female speech is correspondingly shifted upward in frequency. The critical consonant-carrying frequencies for digit discrimination (the fricatives and affricates that distinguish, for example, five from nine, or three from free) lie in the 2 kHz to 4 kHz range, where female speakers typically produce more energy than male speakers relative to the fundamental. In an AM system with a voice audio bandwidth of approximately 300 Hz to 3,400 Hz—the standard for DSB or narrowband AM at the documented station frequencies—a female voice fills this passband more efficiently, placing the maximum spectral energy in the region of greatest intelligibility gain per unit of signal power.

Second, the higher formant frequencies of female speech interact more favourably with the acoustic noise floor of a shortwave AM channel, which is dominated by atmospheric impulse noise with a spectrum that falls off above 2 kHz. A female voice, whose energy distribution extends further into the 2 kHz to 4 kHz region relative to male speech, is thus received at a higher signal-to-noise ratio in the perceptually critical formant region, without any increase in transmitter power. Psychoacoustic research consistently confirms that under degraded-channel conditions analogous to narrowband AM with atmospheric noise, digit and word recognition scores are higher for female speakers than for male speakers at the same channel SNR [11].

The operational conclusion is clear: the choice of a female voice announcer for S02 and E01 represents a considered technical decision to maximise digit intelligibility for the receiving agent under the expected channel conditions, at no cost in transmitter power or equipment complexity.

Comparison with contemporary Western practice: the E14 approach

The intelligibility engineering of the Bulgarian stations is instructive when set alongside the more sophisticated approach documented for the Family 2 CIA/NSA-attributed station E14 (*4F Counting Control*) [28] and its closely related counterpart E05 (*Cynthia*). These stations—believed to have operated from Warrenton, Virginia and Frankfurt am Main—employed an automated female voice with an American accent, identical in both cases, and are distinguished in contemporary monitoring records by what observers described as a *signature rushing air noise* mixed continuously into the audio underneath the voice announcements [29, 30].

This rushing air noise, far from being an artefact or engineering deficiency, is most plausibly an intentional audio processing technique exploiting a well-established perceptual phenomenon. Introducing a steady rushing air noise beneath a voice in narrowband AM

has two beneficial effects in degraded reception conditions. First, it provides the human auditory system with a stable reference against which the speech signal is perceived, reducing the disorienting perceptual effect of intermittent atmospheric impulse noise that characterises HF shortwave channels. A listener encountering heavy atmospheric static punctuated by abrupt quiet gaps finds digit discrimination more demanding than when a steady rushing air noise is present; the brain's auditory scene analysis mechanism performs better against a consistent background than against an unpredictable one. Second, the rushing air noise fills spectral gaps between the digit announcements and between formants, reducing the perception of the channel as "empty" during pauses and maintaining the listener's auditory attention on the incoming signal.

The result is a measurably more intelligible transmission at the same received signal-to-noise ratio—a form of audio signal processing that anticipates, in the context of Cold War shortwave practice, approaches that would later be systematically studied in speech communications engineering.

Additionally, and of fundamental importance to the operational rationale for using any form of speech synthesis rather than a live human announcer, digitalised or synthesised voice possesses a spectral character that is qualitatively distinct from natural human speech and is substantially more resistant to interference and noise.

Natural human speech is produced by a continuous, quasi-random modulation of vocal tract resonances, resulting in a spectrum that varies moment to moment in both amplitude and frequency distribution. The energy is spread across a broad range of frequencies in a pattern that is highly similar, in its statistical properties, to many forms of broadband noise and atmospheric interference. As a consequence, even a relatively weak noise source operating on the same channel—whether atmospheric impulse noise, a co-channel interferer, or deliberate jamming—can obliterate critical speech cues, because the noise spectrum overlaps substantially with the speech spectrum in both frequency and temporal structure. The human auditory system struggles to separate the two signals when their spectral envelopes are similar, and intelligibility collapses rapidly as the noise level approaches the speech level.

Digitalised or synthesised speech, by contrast, exhibits a markedly different spectral signature. Because it is generated from a finite set of stored phoneme or digit samples—each produced under controlled, noise-free conditions and reproduced with machine precision at a fixed amplitude and timing—its spectral energy is concentrated in well-defined, stable, and repeatable patterns. Each digit is acoustically identical every time it is played, with no breath noise, pitch drift, or formant variation between repetitions. The spectrum of a synthesised digit therefore stands out clearly against broadband atmospheric noise, because the noise lacks the structured harmonic relationships and precise formant positioning that characterise the synthesised output. The human auditory system, and particularly a trained listener who has internalised the exact acoustic template of the synthesised digits from repeated exposure, can extract the signal from a noise background

that would render natural speech wholly unintelligible at the same signal-to-noise ratio.

This noise resistance was the primary technical justification for the adoption of synthesised voice in military and clandestine radio operations well before the digital era. It explains why services as different in their resources as the CIA, the East German MfS, and the Soviet GRU all converged on speech synthesis as the preferred output method for number station transmissions: not merely for the operational convenience of unmanned, repeatable broadcasts, but because synthesised speech is intrinsically more intelligible than natural speech under the degraded channel conditions of shortwave AM reception at low signal-to-noise ratios.

The more precisely timed and uniformly enunciated the digit announcements—the more "digital" in character the synthesis—the greater this noise resistance becomes. Slow, regular, machine-paced enunciation additionally reduces the cognitive load of segmenting the digit stream and comparing successive five-figure groups with the agent's one-time pad, compounding the spectral advantage with a perceptual one.

By contrast, the available monitoring records for S02 and E01 do not suggest a comparable level of audio engineering sophistication. The voice quality of these transmissions, as characterised by ENIGMA monitoring logs and the few surviving recordings cited in the Priyom database [17, 18], is consistent with a comparatively primitive speech synthesis approach—likely an early analogue or low-resolution digital device producing a recognisable but unrefined female voice, with no evidence of deliberate noise-floor addition or other audio processing designed to enhance intelligibility under degraded reception conditions. The transmitter modulation depth appears to have been set high—a common practice with valve transmitters of the period, where deep modulation improves AM carrier-envelope fidelity but at the cost of increased susceptibility to overmodulation distortion on voice peaks.

These observations do not invalidate the number station hypothesis; they are entirely consistent with it. An intelligence service with limited access to sophisticated digital voice synthesis hardware—the DDR Gerät 32620 was not widely available outside the MfS until the mid-1980s and later—and operating from a small, low-observable transmitter facility would have relied on whatever voice generation technology was available to it, which in the 1960s and 1970s almost certainly meant analogue tape replay or a simple single-chip speech synthesiser with correspondingly modest output quality. The gap between the audio quality of S02/E01 and that of E05/E14 is not evidence of amateurism; it is evidence of the technological gap between the resources available to Bulgarian state security and those of the CIA during the same period.

7 Frequency cross-check: documented number station transmissions versus Beaumont antenna design bands

7.1 Stations attributed to Bulgaria in the ENIGMA records

The ENIGMA Control List and its successor, the ENIGMA 2000 Active Station List [12], record two number stations for which a Bulgarian origin has been proposed or confirmed by the monitoring community:

> **S02** (*Drums and Trumpets*): A Slavic-language station broadcasting in Bulgarian, operated by Bulgarian intelligence. The preamble consisted of the bugle call *Il Silenzio* (also tracked separately as X01), followed by an automated male and female voice reading five-figure groups. Confirmed inactive since 1996 [17]. Documented transmission frequencies: 4740, 5500, 6675 kHz.
>
> **E01** (*Ready, Ready!*): An English-language station using an automated female voice, attributed by some researchers to Bulgaria on the basis of structural similarities with S02 [18, 31]. Surviving recordings reveal a distinctly Bulgarian accent in the female announcer's English-language digit readings [31], providing one of the stronger circumstantial indicators of Bulgarian origin independent of the frequency and propagation evidence. Its country of origin is unconfirmed; Bulgaria, Italy, and the United States have each been proposed. Inactive since approximately 1999. No ENIGMA newsletter or monitoring log records specific transmission frequencies for E01 independently. The frequencies 4740, 5500, and 6675 kHz are associated with E01 solely on the basis of the suspicion that it shared frequencies with S02; this has not been confirmed by direct monitoring records and must be treated as an inference rather than a documented fact.

Both stations transmitted in AM mode. The three frequencies 4740, 5500, and 6675 kHz are documented for S02 in monitoring records. For E01, no independent frequency records exist in the ENIGMA newsletters or the Priyom.org database; the same frequencies are attributed to it on the basis of the inference of shared scheduling with S02. The propagation and antenna analysis in this study therefore rests on firm ground for S02 and on reasonable but unconfirmed inference for E01. Number station frequency logs from the Cold War period are in any case inherently incomplete, and additional channels may have been used at times not captured in the public record.

7.2 Physical antenna parameters at the documented frequencies

The three frequencies documented for S02—4740 kHz, 5500 kHz, and 6675 kHz—fall in the 60/75 metre and 49 metre shortwave regions. Table 12 presents the principal physical

Table 12: Physical parameters of a cut-delta quadrant scaled to documented Bulgarian number station frequencies, after Beaumont (2015), ref. design at 7.15 MHz: arm outer tip = 14.185 m, $\lambda/4$ height = 10.43 m.

Freq. (kHz)	**Freq. (MHz)**	λ **(m)**	**Arm outer tip (m)**	$\lambda/4$ **height (m)**
4740	4.740	63.3	21.4	15.8
5500	5.500	54.5	18.4	13.6
6675	6.675	44.9	15.2	11.2
Beaumont ref. (7150 kHz)		41.9	14.2	10.4

parameters of a cut-delta quadrant antenna, scaled from Beaumont's reference design at 7.15 MHz [8], for each documented frequency.

All three frequencies require arm lengths between 15 m and 21 m and $\lambda/4$ mast heights between 11 m and 16 m. These are entirely practical dimensions: they closely bracket Beaumont's modelled reference design, and as previously noted in Section 3, satellite imagery confirms mast structures exceeding 10 m at all three candidate sites. The physical infrastructure observed is therefore consistent with, and sufficient for, operation at any of the three documented frequencies.

7.3 Relationship to the commercial HQ quadrant band plan

A comparison of the three documented frequencies against the shortwave broadcasting band allocations listed in the commercial HQ quadrant specification [9] reveals a noteworthy discrepancy: none of the three frequencies falls within a standard WARC-92 shortwave broadcasting band. The nearest standard allocation is the 49 metre band (5.90 MHz to 6.20 MHz); the 6675 kHz frequency lies approximately 475 kHz above its upper edge, and 4740 kHz and 5500 kHz lie entirely below the lowest WARC-92 shortwave broadcasting allocation.

This observation is significant in two respects. First, it confirms that the documented Bulgarian number stations were *not* using standard international broadcasting frequencies, which would have subjected them to ITU coordination and monitoring. By operating in the interstices between allocated bands—in what radio engineers sometimes describe as "interband" or "utility" spectrum—the transmissions avoided the ordinary shortwave broadcast monitoring infrastructure whilst remaining fully audible to any receiver tuned to those channels. This is consistent with established number station tradecraft.

Second, it demonstrates that the commercial HQ broadcast quadrant, designed specifically for the standard WARC-92 shortwave broadcasting bands, was *not* the antenna type employed. Rather, the documented frequencies are consistent with a purpose-tuned quadrant antenna—either a Wells cage quadrant or a Beaumont-style cut-delta—dimensioned

specifically for the operational frequencies, scaled upward in arm length and mast height from Beaumont's 7 MHz reference design.

7.4 Deliberate frequency selection, nighttime propagation, and NVIS geometry: a unified operational argument

The documented operating frequencies of S02—4740 kHz, 5500 kHz, and 6675 kHz—are not an incidental or arbitrary choice. Examined in the context of HF propagation physics, they form a coherent and deliberate operational design whose logic connects frequency selection, solar independence, propagation reliability, transmission scheduling, and target distance into a single unified argument.

Low frequencies and the nighttime propagation window

At the frequencies in question (4.74–6.675 MHz), shortwave propagation is strongly governed by the state of the ionospheric D-layer. During daylight hours, the D-layer absorbs HF energy at these frequencies almost completely, making skywave propagation over distances beyond a few hundred kilometres unreliable or impossible. After sunset, the D-layer rapidly collapses as solar ultraviolet ionisation ceases, and the F-layer becomes the dominant reflecting medium. The result is a well-defined and predictable nighttime propagation window during which signals at these frequencies propagate reliably via single-hop NVIS or near-NVIS skywave to distances of 400 km to 1,300 km.

This nighttime window is not a limitation of the frequency choice—it is its purpose. A number station operates to a fixed schedule known to the agent. If the transmission is reliably audible every evening within a defined window, the agent knows exactly when to listen and for how long. The low frequencies guarantee this reliability: because D-layer absorption at 4.74–6.675 MHz is severe and consistent during daylight, there is no ambiguity about when propagation begins. Twilight at the midpoint of the Sofia–Vienna or Sofia–Istanbul path occurs at a predictable local time, and from that point forward the signal is available. The agent's schedule is therefore as reliable as sunset itself.

Independence from solar activity

Higher shortwave frequencies (above approximately 10 MHz) offer longer daytime propagation paths but introduce a critical operational liability: their usability depends strongly on solar activity. The maximum usable frequency (MUF) for a given path varies with the 11-year solar cycle, seasonal changes, and daily solar flux indices. At solar minimum, a path that requires 14 MHz at solar maximum may only support 9 MHz. An operator who selects a frequency above 10 MHz must monitor solar conditions, update frequency schedules periodically, and accept that on days of elevated solar disturbance the chosen frequency may be entirely unusable.

At 4.74–6.675 MHz, this variability is effectively eliminated. These frequencies lie well below the nighttime MUF for paths of 400 km to 1,300 km under all solar conditions—including the deepest solar minimum. The lowest usable frequency (LUF) at night for these paths is typically below 3 MHz, meaning the entire 4.74–6.675 MHz band is reliably usable regardless of solar flux, season, or geomagnetic disturbance. A single fixed frequency, established once and maintained indefinitely, will propagate reliably to the target on every clear night without any need to adjust for solar conditions. This is the operational simplicity that a clandestine one-way communications channel requires: the agent has one receiver, one frequency, one time. Nothing changes.

NVIS geometry and the target arc

The physical consequence of operating at these low frequencies with a low-mounted horizontal antenna is NVIS propagation: the majority of radiated energy departs at high elevation angles, reflects from the F-layer at near-vertical incidence, and returns to ground within a radius determined by the reflection height and the launch angle distribution. For a horizontal antenna at $\lambda/4$ to $\lambda/2$ height, the single-hop NVIS footprint at 4.74–6.675 MHz covers a radius of approximately 400 km to 1,300 km—precisely the range band within which Vienna, Munich, Rome, Istanbul, Athens, and Nicosia all fall from Sofia (Table 6). This is not a coincidence. The frequency was selected to make NVIS the propagation mechanism, and the NVIS mechanism covers exactly the distances at which the agents were located.

Conversely, the frequency selection actively *excludes* longer-range propagation. At 4.74–6.675 MHz, a single-hop skywave path to a monitoring station at 3,000 km to 4,000 km distance (Western Europe or the United States) is not supported at night: the skip distance for these frequencies at nighttime F-layer heights is typically less than 1,500 km, and signals beyond that distance would require multiple hops with corresponding attenuation. A SIGINT monitoring station in London or Washington attempting to intercept these transmissions would receive a substantially weaker signal than the intended agent in Vienna or Istanbul—a further consequence of the frequency selection that benefits operational security.

The antenna as the matching element

The VGDSh and its Western equivalent, the quadrant, are the natural antenna complements to this frequency and propagation strategy. Both are horizontal, low-mounted antennas whose elevation patterns peak at or near the zenith at $\lambda/4$ mounting height, directing the majority of their radiated energy into the NVIS cone. A high-gain directional curtain array, by contrast, would concentrate energy at low elevation angles, wasting the majority of its power into oblique skywave paths that bypass the intended coverage zone entirely—exactly the wrong radiation pattern for the intended propagation mode. The

antenna, the frequency, and the propagation mechanism are therefore mutually consistent and mutually reinforcing design choices, each selected to serve the same operational objective.

Physical dimensions at the documented frequencies

At 4740 kHz, a VGDSh or cut-delta quadrant requires arm dimensions scaled upward from Beaumont's 7.15 MHz reference: arm outer tips at approximately 21 m and $\lambda/4$ mounting height of approximately 16 m. At 6675 kHz, these reduce to approximately 15 m and 11 m respectively—closely bracketing Beaumont's reference design (14.2 m arm tips, 10.4 m mounting height). All three frequencies are therefore accommodated by mast heights in the range 11 m to 20 m, consistent with the infrastructure observed at the candidate sites and well within the scope of standard military lattice mast construction.

Beaumont's cut-delta quadrant at 7.15 MHz was designed, in his own words, to yield "approximately constant field strength, independent of distance, for signals out to about 1,500 km, i.e. a single ionospheric hop" [8]—a coverage objective that is identical to the operational requirement of the Bulgarian number station transmissions as inferred from their documented frequencies and target geography.

7.5 Interim conclusion

The documented operating frequencies of S02 and E01 represent a deliberate and coherent engineering choice whose full logic is revealed only when frequency selection, solar independence, propagation reliability, antenna geometry, and target distance are considered together. The low frequencies (4.74–6.675 MHz) guarantee nighttime propagation reliability independent of solar conditions; the nighttime-only window provides a predictable and operationally convenient transmission schedule; the NVIS propagation geometry at these frequencies covers exactly the target arc from Sofia; and the VGDSh or equivalent horizontal low-mounted antenna is the natural complement to this propagation mode. These are not independent coincidences but a unified operational design. The frequencies lie outside the standard WARC shortwave broadcasting allocations—avoiding ITU coordination and routine broadcast monitoring— whilst remaining fully usable for the intended purpose on every clear night of the year, regardless of the solar cycle.

8 Conclusions

The following conclusions are drawn from the foregoing analysis. Given that the Bulgarian Government has never published any official information on number station operations—unlike the Czech and Polish governments, which have released relevant documentary evidence—all conclusions are necessarily inferential and probabilistic in character.

1. The Bulgarian transmitter sites under study were equipped with Soviet-pattern VGDSh-family horizontal dipole antennas, not quadrant antennas. The VGDSh family comprises three principal configurations: the single-element VGD/VGDSh (bi-directional azimuth pattern), and the dual-element VGDSh-2U (two dipoles at 90°, near-omnidirectional when fed in quadrature). All members of the family are horizontally polarised, all are mounted at low height, and all therefore share the same NVIS propagation mechanism and produce identical elevation patterns at the same mounting height. Russian engineering literature explicitly designates the VGDSh as a zenith-radiation (NVIS) antenna [3]. Because the precise variant installed at each Bulgarian candidate site cannot be determined from open sources, and because VGDSh specifications are inconsistently documented in the public domain, this study uses the quadrant—rigorously characterised by Beaumont [8]—as an analytical proxy. All link budget figures, minimum power calculations, and NVIS coverage conclusions are directly applicable to any member of the VGDSh family at the same mounting height and frequency. The azimuth pattern is the only property that varies: a single-element VGDSh requires careful wire orientation to avoid end nulls, whilst the VGDSh-2U and the quadrant both achieve near-omnidirectional coverage by the same fundamental principle of crossed dipole elements at 90°.

2. The near-omnidirectional azimuth pattern of the quadrant antenna confers a significant additional operational advantage: resistance to direction-finding. Conventional DF techniques exploiting azimuth signal variation cannot form a meaningful bearing estimate against a transmitter whose azimuth gain varies by only $\pm 0.9\,\mathrm{dB}$ across the full 360°. The resulting bearing uncertainty of $\gg 10°$ translates to a cross-range position uncertainty exceeding 160 km at 900 km range (Section 6.3), larger than the entire Sofia region. This is consistent with the ENIGMA community's attribution of S02 and E01 to Bulgaria as a country without being able to identify any specific transmitter site—a level of precision that could not have been improved upon with the equipment available to civilian monitoring organisations during the Cold War.

3. Horizontally polarised quadrant antennas, whether in the Wells cage or single-wire cut-delta configuration, are technically well suited to the propagation of clandestine shortwave number station transmissions from the Sofia region of Bulgaria. The omnidirectional azimuth pattern of the quadrant is its defining operational advantage: a single fixed antenna simultaneously addresses the north-western arc (Austria, Germany, Switzerland, Italy) and the south-eastern arc (Turkey, Greece, Cyprus, Israel)

without beam switching or multiple installations.

4. The documented transmission frequencies of S02 and E01—4740 kHz, 5500 kHz, and 6675 kHz—represent a deliberate and coherent operational design, not an arbitrary selection. These frequencies lie in the 60–45 metre band, below all standard WARC-92 shortwave broadcasting allocations, and are characterised by two properties that make them uniquely suitable for clandestine number station use: (a) they support reliable single-hop NVIS skywave propagation only during nighttime and twilight hours, providing a predictable and consistent transmission window without any dependence on solar activity or MUF tracking; and (b) their NVIS footprint at the documented antenna heights covers a radius of 400 km to 1,300 km—exactly the range band within which the primary target cities (Vienna, Munich, Rome, Istanbul, Athens, Nicosia) lie from Sofia. The antenna type, the frequency, and the propagation mechanism are mutually consistent and mutually reinforcing design choices. A purpose-scaled VGDSh or quadrant at these frequencies requires arm lengths of 15 m to 21 m and mast heights of 11 m to 16 m—dimensions consistent with mast infrastructure observed at all candidate sites.

5. Applying the correct operational criterion—digit intelligibility for a trained agent, not broadcast quality—the minimum transmitter power for the primary target arc is 5 W to 25 W. In practice, standard Warsaw Pact fixed-installation HF transmitters of the Cold War period were rated at 500 W to 1 kW, representing the normal equipment complement of any permanent military or state security communications post. At 500 W to 1 kW, the link margin above the intelligibility threshold for the Vienna path exceeds +40 dB—far above requirement, but consistent with operation at rated power on standard equipment rather than at artificially reduced output. The moderate-to-weak signal strength recorded for S02 and E01 by Western monitoring organisations is consistent with this power range at the monitoring distances involved, and is not consistent with the multi-hundred-kilowatt outputs of the jamming and broadcasting infrastructure at Kostinbrod or Padarsko. No high-power number station transmission attributable to Bulgaria has been recorded. The signal evidence points to equipment in the 500 W to 1 kW class, which leaves no infrastructure signature distinguishable from routine military HF communications.

6. All six primary sites in Table 3 (upper group) are *technically capable* of supporting number station operations. The three primary candidate sites (Pobit Kamak, Gorna Malina, Momina Skala) are assessed as the most *operationally plausible* on grounds of power economy, infrastructure simplicity, and low observability. The high-power sites (Kostinbrod, Padarsko, Stolnik) cannot be categorically excluded: the dual-use character of all Warsaw Pact shortwave infrastructure means that a narrowband low-power transmission could in principle have operated from within any of these perimeters alongside the primary schedule, without being distinguishable from routine transmitter artefacts by external observers. The eight additional sites

examined in Section 3.7 (lower group of Table 3) are assessed as implausible number station candidates: they are dominated by ground-wave jamming installations characterised by low-mounted VGDSh antennas, power profiles inconsistent with the observed signal characteristics of S02 and E01, or impractical relay distances from Sofia.

7. Near-field and parasitic emissions from high-power transmitter sites— direct ground-wave radiation within the antenna near field, harmonic and intermodulation products from valve-based transmitters, and stray feeder radiation from imperfectly balanced open-wire transmission lines—provide a credible physical explanation for unusual shortwave signals reported by residents in the vicinity of these installations during the Cold War period. Such near-field reception does not confirm intentional clandestine broadcasting, but it illustrates that any of these sites could have hosted a covert narrowband transmitter without it being identifiable as such by local witnesses.

8. Gorna Malina remains the most favourable of the primary candidate sites on propagation, logistical, and concealment grounds. Momina Skala is the most favourable for coverage of more distant targets using a stacked quadrant configuration.

9. The fundamental conclusion of this study is one of *technical feasibility across all sites, operational plausibility at the three primary candidate sites, and irresolvable ambiguity on attribution.* The latter can only be resolved by access to Bulgarian State Security (DS) archives, which remain largely classified or "missing". In the absence of such access, this study establishes the RF engineering case that the identified Sofia-region sites possessed the physical infrastructure, the propagation geometry, and the power capabilities consistent with the documented characteristics of Bulgarian-attributed Cold War number station transmissions.

Acknowledgements

The authors gratefully acknowledge the technical data and antenna modelling results published by R. Beaumont (VK2KRB) in Technical Report 014-AR (2013–2015), which provided the principal basis for the single-wire cut-delta quadrant analysis herein, and the publicly available specification data for the commercial HQ quadrant antenna published by antenna.be.

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